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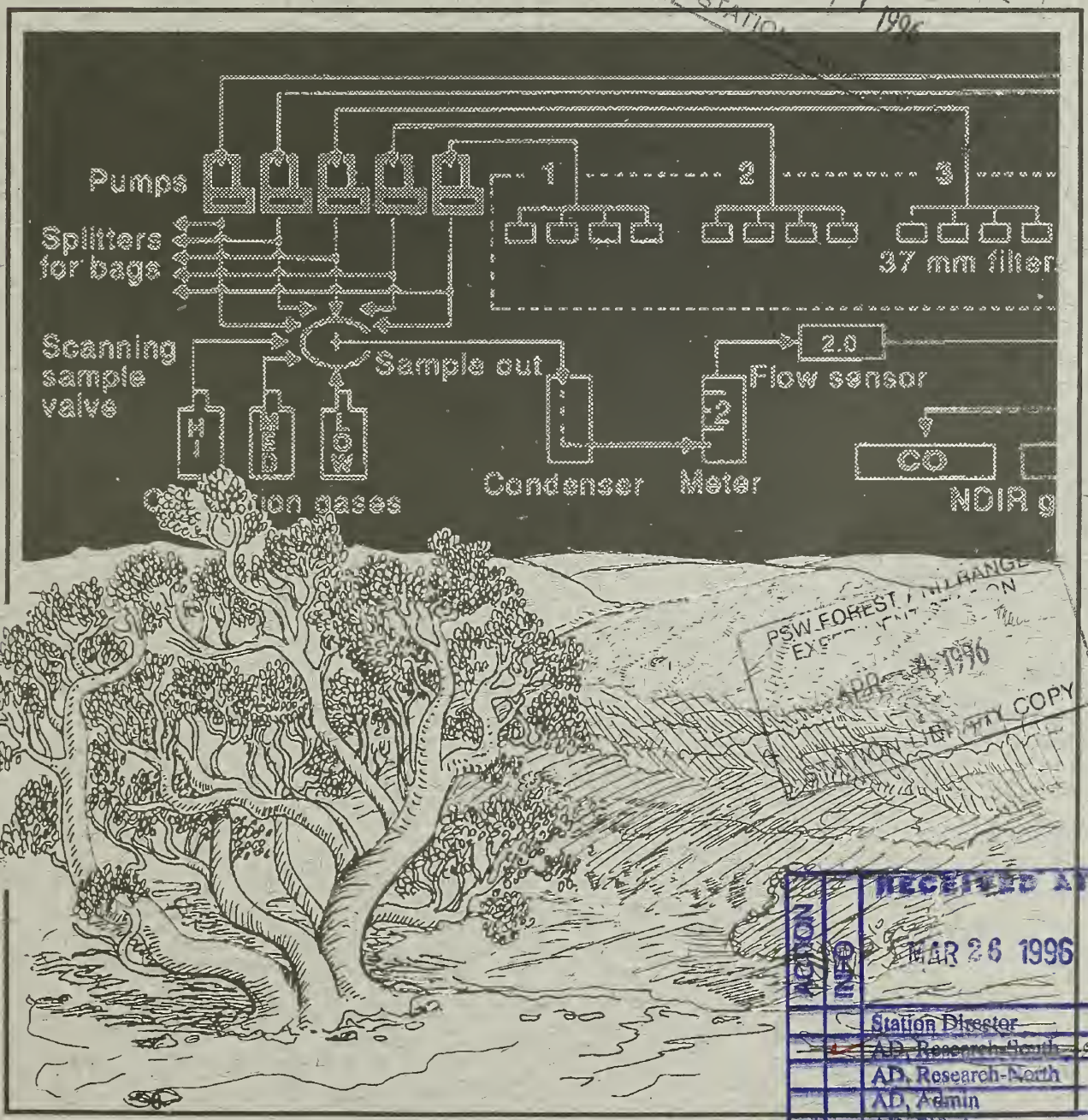

**Authors**

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## Abstract

**Hardy, Colin C.; Conard, Susan G.; Regelbrugge, Jon C.; Teesdale, David R. 1996.** Smoke emissions from prescribed burning of southern California chaparral. Res. Pap. PNW-RP-486. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 37 p.

This report characterizes smoke emissions from small-scale prescribed burns in southern California chaparral. In situ measurements of smoke emissions were made from 12 fires. Three replicate tests were performed in each of four distinct fuel and fire treatments common to vegetation management operations: a young and rigorous chamise-dominated stand; an old and decadent chamise-dominated stand; an old chamise-dominated stand after crushing; and a stand consisting mainly of old ceanothus. Emission factors for total particulate matter, particulate matter 10 micrograms in size and less, particulate matter 2.5 micrograms in size and less, carbon monoxide (CO), carbon dioxide ($CO_2$), methane, and nonmethane hydrocarbons have been developed from the tests. In addition, combustion efficiency and the rates of fuel consumption and heat release were derived from real time measurements of CO, $CO_2$, temperature, and vertical mass flux. The highest combustion efficiencies observed for the flaming phase were from tests at the crushed sites, where most flaming phase emission factors were lower than for the other areas. These results suggested positive management implications for crushing. Emission factors from previous tests in untreated (standing) chaparral are combined with the present data, and the average values from the combined tests are provided for general use in describing smoke emissions from standing chaparral in southern California.

Keywords: Emission factor, smoke emissions, chaparral, prescribed burning, smoke management.

## Summary

Emission factors for total particulate matter (PM), particulate matter 10 µg in size and less (PM10), particulate matter 2.5 µg in size and less (PM2.5), carbon monoxide (CO), carbon dioxide ($CO_2$), methane ($CH_4$), and nonmethane hydrocarbons (NMHC) have been developed from measurements of smoke emissions from 12 prescribed burns in southern California chaparral. Three replicate tests were performed in each of four distinct fuel and fire regimes to represent a range of chaparral fuel types and management treatments: a young and thrifty chamise-dominated stand; an old and decadent chamise-dominated stand; an old chamise-dominated stand after crushing; and a stand consisting mainly of old ceanothus.

Results from the present study also are combined with data from a previous study to form the most complete set of data available for management to use in making decisions on the impacts of prescribed burning on the air resource. The following values are averages from the combined tests and are provided for general use in describing emissions from standing, untreated chaparral.

| | Weighted-average emission factors | | | | | | |
|---|---|---|---|---|---|---|---|
| **Phase** | **PM** | **PM10[1]** | **PM2.5** | **CO** | **$CO_2$** | **$CH_4$** | **NMHC** |
| | *Pounds per ton (±SE)* | | | | | | |
| Flaming | 31.6±2.6 | 16.5 | 13.5±1.1 | 119.2±10.9 | 3326.2±14.6 | 3.4±0.5 | 17.2±6.8 |
| Smolder | 40.0±4.1 | 24.7 | 21.6±2.1 | 197.2±33.9 | 3144.1±34.1 | 9.0±0.3 | 30.6±14.4 |
| Fire[2] | 34.1±3.7 | 20.1 | 17.3±1.2 | 153.7±13.6 | 3257.9±39.7 | 5.7±1.2 | 19.6±8.3 |

In addition, combustion efficiency and the rates of fuel consumption and heat release were derived from real-time measurements of CO, $CO_2$, temperature, and vertical mass flux.

The highest combustion efficiencies observed for the flaming phase were from the Newhall crushed tests, where flaming phase emission factors for CO, PM, $CH_4$, and NMHC were lower than for the other areas. These results suggest positive management implications for crushing. Old ceanothus had higher fire-average PM, $CH_4$, and NMHC emissions than any other treatment studied.

The emission factor for $CH_4$ is inversely related to combustion efficiency ($R^2 = 0.91$). The coefficients of this relation are similar to $CH_4$-to-combustion efficiency relations from tests in other fuels. Theoretically, a carefully executed prescription increasing combustion efficiency by 5 percent can reduce the $CH_4$ emission factor by as much as 50 percent.


[1] PM10 was not measured; it was derived from known PM2.5-PM size class distributions.

[2] "Fire" is an average of flaming and smolder phases weighted by consumption.

## Contents

## Introduction and Background

### Chaparral Vegetation Management

The use of prescribed fire is generally believed to be critical to the effective management of chaparral. A skillfully applied prescribed fire program has the potential to mitigate fire hazard, protect high-value ecosystems and watershed resources, and help protect structures and lives at the wildland-urban interface. Dougherty and Riggan (1982) have described the potential benefits of a large-scale age class management program using prescribed fire to reduce the likelihood and potential impacts of severe wildfires. Maintaining a 20- to 40-year rotation through such a chaparral management program would require burning about 300,000 acres a year in chaparral stands throughout California, probably an order of magnitude greater than the amount burned under current programs (the California Department of Forestry and Fire Protection averaged 42,083 acres State-wide in all types of vegetation over the 12 years from 1981 to 1993).[1] Although a program of the scale Dougherty and Riggan propose has thus far proved impractical, more narrowly targeted programs to reduce hazard in the wildland-urban interface and to break up large expanses of mature chaparral in strategic areas may be quite effective in reducing wildfire damage.

Attention recently has focused on the potential exacerbating effects on fire hazard of dieback of certain shrub species in chaparral (Riggan and others 1994). Immediate effects of dieback and stand decadence are seen in the greatly increased levels of dead fuel in affected communities. Recent research has been undertaken to better understand and characterize stand condition. Paysen and Cohen (1990), for example, question the historically accepted, age-dependent model used to predict the dead fuel fraction of chaparral. Urban encroachment also makes wildfire more costly and more hazardous than in the past. In many areas, we would expect careful application of prescribed fire to provide a safer and less costly approach to fuel management than wildfire. All these factors underscore the need to maintain or increase application of prescribed fire.

No adequate fuel models or consumption algorithms are presently available for use in prescribed fire planning in California chaparral. Reasons for disappointing results from fire behavior predictions include lack of knowledge of extrinsic properties of the fuel carrying the fire (Albini and Anderson 1982). The most extensive development of biomass predictive algorithms is reported in Riggan and others (1988), where biomass of ceanothus (*Ceanothus crassifolius* Torr.), scrub oak *(Quercus berberidifolia)*, and chamise (*Adensostoma fasciculatum* H. & A.) was predicted from areal estimates. Biomass for a species differed by a factor of three or four, depending on location. This variation illustrates the challenge to development of predictive tools useful in emissions production models.

### Smoke Management Considerations

Even though the effectiveness of fire as a management tool is widely accepted, the impact of burning chaparral on the air resource is not well documented. Both chaparral managers and air resource managers need reliable descriptors of the source strength of emissions and regional emissions load from prescribed burning of chaparral.

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[1] Units of measure shown may be either metric or English, depending on the most frequently used convention for the particular parameter described. See "Converstion Factors" at end of text.

Presently, many managers describe "activity level" as the number of acres prescription burned, and simply multiply the acres by a generalized emission factor. Peterson and Sandberg (1988) note that an effective smoke management and emissions inventory program uses a combination of three elements to describe a prescribed burning activity level: (1) the area to be burned (acres) in each unique fuel or fire situation; (2) the preburn fuel loading profile (tons/acre); and (3) a prediction of the mass of fuel consumed for all fuelbed components (tons/acre). The prescribed burning activity level is then expressed in tons of fuel consumed per acre burned and is multiplied by a fuel- and fire-specific emission factor to describe the mass of emission produced per acre burned. A primary objective of the present study is to provide fuel- and fire-specific emission factors for southern California chaparral.

## Emissions Research

Ward and Hardy (1984), in their research on emissions from broadcast burning of logging slash dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), successfully applied the carbon mass-balance procedure to relate measured concentrations of the major carbon-bearing emission species to the rate and amount of fuel consumed. The mass and concentration of several sizes of particulate matter are measured, as are concentrations of several primary combustion-product gases: carbon monoxide (CO), carbon dioxide ($CO_2$), methane ($CH_4$), and nonmethane hydrocarbons (NMHC).

Emission factors derived from the carbon mass-balance procedure describe the mass of emission produced per unit mass of fuel consumed and are reported in pounds per ton or grams per kilogram. The carbon mass-balance procedure applied to grab and continuous samples and the quantification of the fuel consumption associated with each also has been described by Ward,[2] Ward and Hardy (1984), and Ward and others (1982). Nelson (1982) tested the carbon mass-balance method under laboratory conditions and determined that the difference in fuel consumption with carbon mass-balance and weight loss measurements using a load-cell weighing platform is less than 15 percent. Radke and others (1990) successfully used carbon mass-balance methods with airborne sampling of emissions from prescribed fires. Carbon mass-balance methods have been used extensively and form the primary techniques of quantifying the fuel consumed relative to the emissions produced during this study.

Average emission factors for three size classes of particulate matter were summarized from several sources by Ward and others (1988). The emission factors were prepared to represent fuel conditions in five distinct regions of the United States. Emission factors were reported for PM, PM2.5, and PM10 (particulate matter less than 10.0 µm mean mass cutpoint diameter). It should be noted that PM10 values were not obtained empirically. Rather, they were derived from PM-to-PM2.5 ratios by using known size-class distributions of particulate matter, as described by Radke and others (1990). (See appendix 2 for information on these calculations.)

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[2] Ward, D.E. 1981. Emissions from the combustion of residual fuels. Study plan PNW-81-1-(B-1). On file with: Pacific Northwest Research Station, Forestry Sciences Laboratory, 4043 Roosevelt Way NE, Seattle, WA 98105-6497.

In 1989, the differences in emissions between prescribed burns in Douglas-fir/western hemlock (as described by Ward and Hardy 1984) and five previously unstudied fuel types were examined by Ward and others (1989). The additional fuel types considered included coastal hardwoods, long-needled pine, mixed conifer, and burns of crane-piled slash and tractor-piled slash.

Hardy and Teesdale[3] have reported results from emissions research in two range-type fuel complexes: basin big sage (*Artemisia tridentata* Nutt.) and western juniper (*Juniperus occidentalis* Hook.). The research was designed to investigate potential differences in emissions characteristics between fall and spring burning prescriptions. Few significant differences in emissions were found between the two prescriptions.

Smoke emissions from chaparral fires have been measured by using combustion hood experiments, surface-based sampling systems, and aircraft-borne samplers.[4] Weise and others (1991) examined CO, $CO_2$, and particulate emissions from test fires of several chaparral species burned on a vented burning table. The objective of their study was to determine the effect(s) of species and month on chaparral smoke emissions. Airborne sampling of chaparral emissions has been accomplished by three different research teams on two fires within the same prescribed burning project in 1987 (the Lodi project): Radke and others (1991) sampled trace gas and particulate emissions by using a twin-engined C-131; Einfeld and others (1989) sampled particulate and trace element production using a Twin Otter; and Cofer and others (1989) sampled trace gas emissions with a helicopter. Ground-based, in situ sampling of the emissions from three small tests within the Lodi project was accomplished by Ward and Hardy (1989) prior to the main burn. They compared the smoke characteristics from the chaparral tests to data from the Pacific Northwest. Emission factors for carbon monoxide were only 50 percent of the Pacific Northwest emission factors. Concentrations of certain trace materials contained with the PM2.5 were much higher in chaparral smoke. Lead, for example, made up nearly 0.34 percent of the PM2.5 for chaparral but was less than 0.10 percent for logging slash. Before the present study, the three tests comprised the only ground-based source measurements of emissions from prescribed burning of chaparral.

## Objectives

The primary objectives of this study were to measure and characterize the source emissions from prescribed burning over a range of vegetation structure and treatment conditions; determine if management options could be identified that mitigate smoke production; and determine whether generalizations useful for regulatory and planning purposes could be made concerning emissions from chaparral fuels.

The study design for the tests discussed in this report required three replicate tests performed in each of four distinctly different age-class and treatment regimes. Through assessments of preburn biomass, fire variables, burning prescriptions, and postburn biomass, the design allowed exploration of relations among emissions produced with fuel and fire variables.

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[3] Hardy, C.C.; Teesdale, D.R. 1990. Smoke emissions from prescribed fires in western juniper and basin big sagebrush of central Oregon. Final report. On file with: Pacific Northwest Research Station, Forestry Sciences Laboratory, 4042 Roosevelt Way NE, Seattle, WA 98105-6497

[4] Ward and Radke (1993) present a comparative discussion of the general advantages and disadvantages of each of these three approaches.

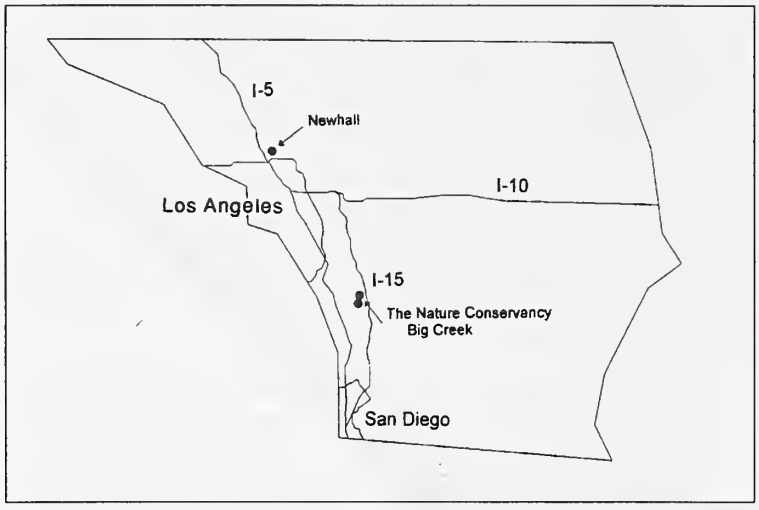


Figure 1—Locations of the test sites in southern California. The Newhall sites were in northern Los Angeles County, and The Nature Conservancy (TNC) and Bear Creek sites were west of I-15 between Los Angeles and San Diego.

## Study Design

The source characteristics of smoke emissions were measured from three replicate test burns in three chaparral stands with different structural characteristics. In one stand, half of the six test plots were mechanically crushed and cured before burning. The null hypothesis for this study was that no significant differences in the characteristics of emissions could be detected between stands having various structure and treatment regimes.

Four selection criteria were used to establish feasible test areas:

**1.** Typical chaparral stands of different ages, species, and structural composition.

**2.** Test areas, treatments, and burning prescriptions represent conditions expected in operational vegetation management strategies.

**3.** The three test areas, along with crushing of the vegetation on a fourth area, effectively represent four distinctly different fuel and treatment regimes.

**4.** Cooperation with ownership and management ensures the highest probability of success.

Three replicate subunits were established for each of the four treatments. The replicates were burned and sampled individually to provide three independent observations. To minimize variability in fuel and fire conditions, the tests on a given site were executed on the same or consecutive days.

### Test Area Selection and Descriptions

Three areas were selected in southern California (fig. 1): (1) young chamise (The Nature Conservancy [TNC]); (2) mature ceanothus mixed with chamise (Bear Creek); and (3) mature chamise (Newhall). At Newhall, three of the six subunits were assigned to be crushed by tractor before burning (Newhall crushed). Vegetation on the other three subunits was left standing (Newhall standing) as at the other sites. Each test area is described in table 1. Refer to figures 2 through 4 for subunit layouts.

**Table 1—Location, physical description, and vegetation composition of the four treatment areas**

| Treatment area name | Location of area | Aspect | Elevation above msl[a] | Age of vegetation | Dominant species[b] |
|---|---|---|---|---|---|
| | *Lat./long.* | | *Feet* | *Years* | |
| TNC | 32° 32' 15"N.<br>117° 15' 30"W. | north to west | 2,100 | 10 | ADFA<br>QUBE |
| Newhall crushed | 34° 29' 24"N.<br>118° 33' 42"W. | south | 1,700 | 35-50 | ADFA (dozer-crushed) |
| Newhall standing | 34° 29' 24"N.<br>118° 33' 42"W. | south | 1,700 | 35-50 | ADFA |
| Bear Creek | 33° 33' 00"N.<br>117° 16' 00"W. | east | 1,800 | 30-50 | CECR<br>ADFA |

[a] Msl = mean sea level.
[b] Species identification: ADFA = *Adenostoma fasciculatum* (chamise); CECR = *Ceanothus crassifolius* (ceanothus); QUBE = *Quercus berberidifolia* (scrub oak).

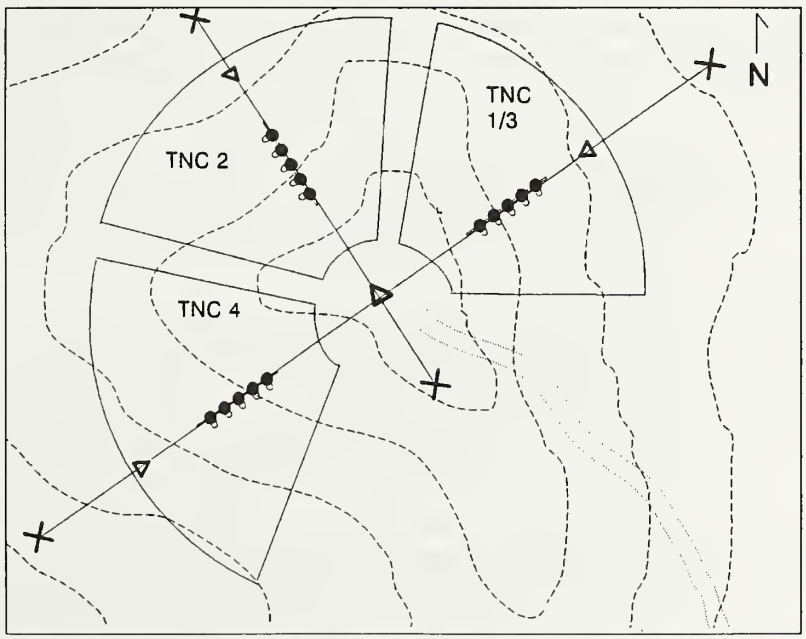


Figure 2—Layout of The Nature Conservancy test plots. The plots were centered around the top of a small hill.

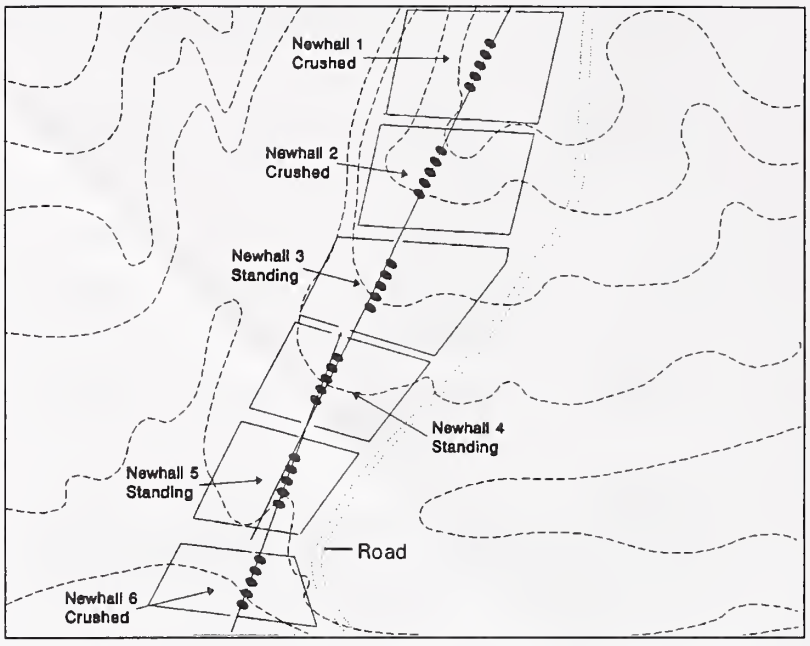


Figure 3—Layout of the Newhall test plots. Newhall 1 was on the top of a knoll with elevation decreasing toward Newhall 5. Newhall 6 was across a gravel road from the other sites.

The TNC subunits were located in the Santa Rosa Plateau Preserve (see fig. 2). The area was dominated by young, healthy chamise, 10 to 15 years old, and 2 to 5 ft tall, with scrub oak individuals. A large amount of dead fuel in the ½-in-and-greater size classes remained from a previous fire. Subunits were located on a crowned knob, with aspects north to west and slopes of 15-20 percent. The site was well drained and exposed to both easterly and westerly winds. Burning prescription for this young, healthy stand required an upper limit live fuel moisture of 60 percent, with relative humidity less than 30 percent. An optimal prescription would require burning this area under relatively hot, dry conditions. Gradient winds of 5 to 15 mi/h would benefit fire spread.

The chamise at the Newhall units was mature, about 35 to 50 years old. Three subunits were treated by crushing (trampling) with a crawler-tractor, thereby reducing the fuel depth to about 12 to 18 in. The remaining three units were left standing (fig. 3). Crushing was performed in spring 1989. On all units (before crushing), the standing dead fuel fraction was about 32 percent with moderate herbaceous cover. Average crown height on all units (before crushing) was 4.6 ft. The site was well drained with 15 percent slope and southerly exposure. At the time of burning, the chamise vegetation on the crushed units was dead and had been cured for 12 months. The subunits therefore could be burned much earlier (or later) than standing areas—the burning window was not constrained by live fuel moisture. The crushed subunits could be burned before the standing subunits, prior to depression of standing live fuel moistures. The prescription objectives for the standing subunits were to create the highest possible fire intensities within reasonable control considerations. The entire perimeter of the standing subunits was to have been treated by crushing and burning to establish a black line around the remaining subunits before burning the standing subunits.

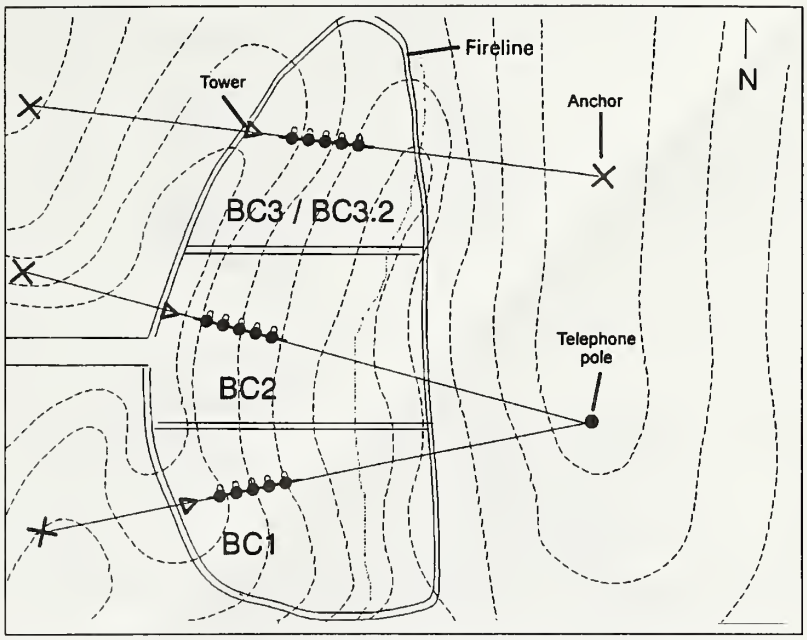


Figure 4—Layout of the Bear Creek burns. The plots were on the side of a steep hill. The plots increase in altitude, in this representation, as one progresses from the right to the left.

The vegetation at the Bear Creek units consisted of mature ceanothus and chamise—6 to 10 ft tall with more than 20 percent dead material (see fig. 4). Aspect was easterly, with steep (50-65 percent) slope. The site was sandy and well drained. Litter had accumulated in pockets on the steep slopes. There was little or no herbaceous material.

Due to steep slopes and high fuel loads, the Bear Creek units were expected to burn well under a wide range of conditions. The area could be burned in late spring or early summer—earlier than most areas.

## Research Methods

### Fuel and Biomass Assessment

Stand biomass and fuel characteristics were estimated for each subunit within each site before burning to investigate relations between emissions and fuel variables. A two-stage sampling approach was used to avoid altering the fuel structure of the test sites. Nondestructive measurements of shrub dimensions were recorded for plots within the test areas, and destructive sampling of shrubs adjacent to the test areas was used to develop models for estimation of fuel variables from the dimensional measurements.

Two 2- by 10-m plots were established in each unit. All shrubs on each plot were tallied by species, height, canopy depth, and canopy diameter. Additionally, basal diameter and status (live or dead) was recorded for every stem of each shrub.

Twenty to fifty stems were harvested for each species and status at each site, and were partitioned into live wood, dead wood, and foliage components. These stems were selected to be approximately evenly distributed throughout the range of stem basal area found on the plots. Regression analysis was used to develop models for predicting biomass components of shrubs from shrub dimensions.

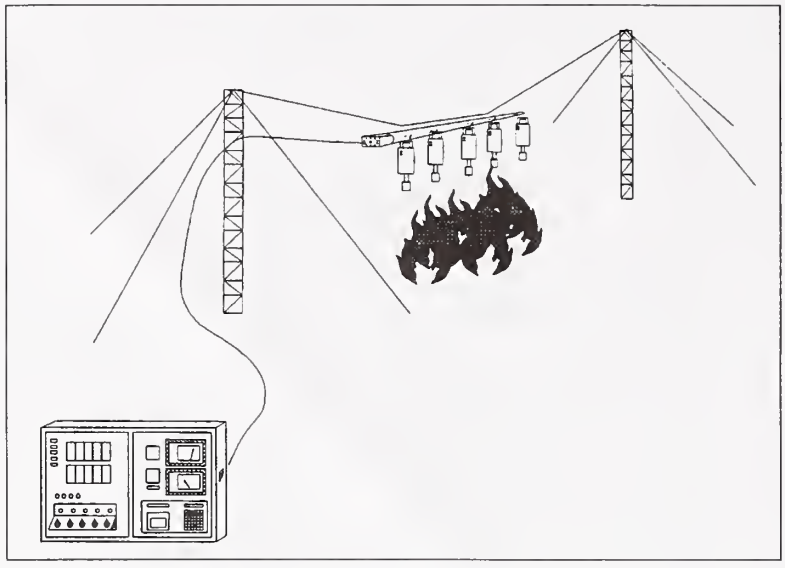

Figure 5—A schematic of the steel tower-and-cable support system suspending the sampling system over a test burn.

Biomass components were estimated for each burn unit by substituting dimensional measures recorded on plots into biomass estimation models developed from destructive sampling. Biomass component estimates for stems were summed across plots, converted to a unit area basis by dividing by plot area, and averaged over plots to obtain estimates for each burn unit. The mean of the three burn units yields the average for each site. Biomass components estimated include total fuel loading (total aboveground biomass), live stemwood, foliage, attached dead wood (dead branches on live stems), standing dead wood (standing dead stems), total dead fuel, and dead fuel fraction (total dead fuel over total fuel).

After the test burns, we harvested all residual plant biomass on the plots to estimate fuel consumption by subtracting residual fuel from the estimates of prefire fuel loading.

**Instrumentation**

The emissions sampling system was designed to obtain real-time, continuous measurements of the flux of emissions and to simultaneously collect grab samples of emissions from the prescribed fires during specific periods.

Five identical instrumentation packages (sample packages) were suspended from a steel tower-and-cable support system and were positioned directly above the active combustion plume (fig. 5). All five packages were connected through a 200-ft vacuum hose and electrical umbilical to a remote control platform (figs. 6 and 7). Specifications for instrumentation used are given in appendix 1.

Where possible, discrete grab samples were collected for two combustion phases: flaming and smoldering. For each phase of combustion, grab samples of both particulate matter and gases were obtained from each of the five sampling packages.

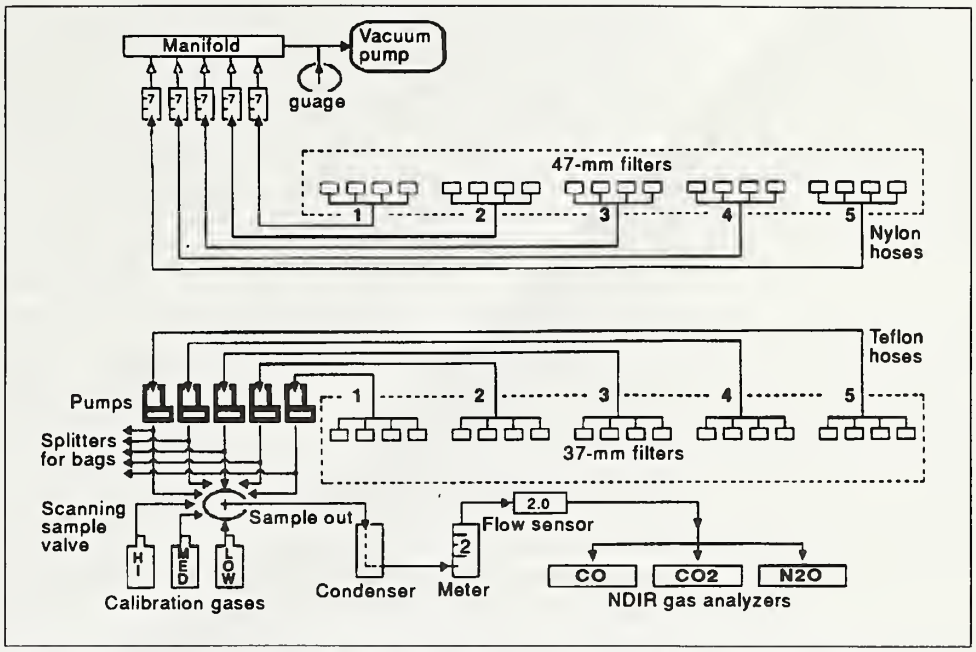


Figure 6—Schematic of the tubing and gas-train configuration used for real-time measurement and grab sampling of emissions.

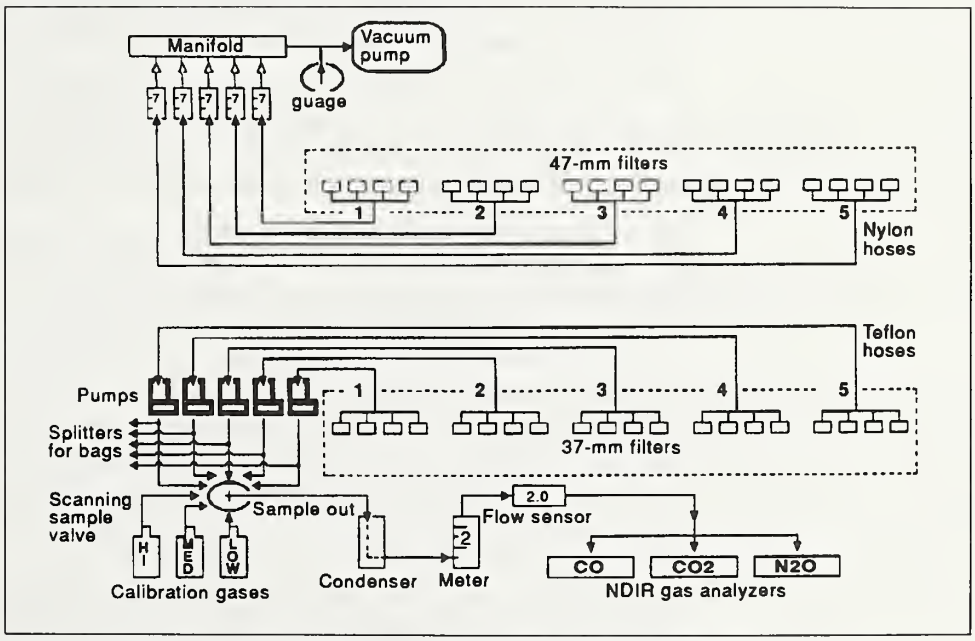


Figure 7—Schematic of analog-to-digital input/output and electrical configuration for real-time sampling system.

**Particulate matter sampling**—Particulate matter was sampled for each phase of combustion on three kinds of filter media in two different sizes (and volume flows). Paired samples of particulate matter were taken at each package—one of total particulate matter (PM), and the other of particulate matter with particle diameters of less than 2.5 µm mean mass cutpoint diameter (PM2.5). Each of the five sample packages was fitted with four sets of filters; each set consisted of one 47-mm filter head and one 37-mm filter head. A rotating valve and cover device was used to obtain discrete particulate samples for flaming and one or more smoldering combustion phases on separate sets of filters. All the filter-set selecting and sample volume adjustments were controlled and monitored from the ground station.

The 47-mm filter heads on each sample package held glass-fiber filter mats. A high-capacity rotary vane vacuum pump was used to supply a constant flow of about 7 l/min through the 47-mm filter heads. The vacuum was ported to the filter heads through a manifold and five nylon hoses (fig. 6) and was regulated by maintaining a differential pressure across flow-limiting orifices of at least 0.56 atmosphere.

The 37-mm filter holders used a cyclone presampler to provide a mean mass diameter cutpoint of 2.5 µm. For each combustion phase, the 37-mm filter holders on three of the packages contained glass-fiber filters; the remaining two packages held filters of stretched Teflon with polyolefin rings.[5] Five 24-volt direct current (dc) diaphragm pumps were used to supply vacuum through individual Teflon hoses (fig. 6) to the 37-mm filter holders on each sample package. A constant volume flow of 2 l/min was maintained throughout the sampling period with low-pressure regulating valves and by controlling the voltage to each respective pump.

Flow rates were referenced to a calibrated rotameter and to an electronic flow sensor. Flow rates and subsequent volume calculations were corrected to standard temperature and pressure (STP). The difference in temperature and pressure between laboratory calibration of the rotameter and field use also was accounted for.

**Combustion gases**—Gases were sampled at the ground station from each of the five Teflon tubes connected to the sample packages. For each phase of combustion, flow-restricting splitter outlets were used to collect a portion (0.05-0.20 l/min) of the 2-l/min sample volume from each package in 5-l aluminized-Mylar gas sample bags. The remainder of the 2-l/min gas stream from each package was ported to a scanning sample valve (scanivalve). The scanivalve sequentially directed each gas stream (25 seconds per package) through a divider to two nondispersive infrared gas analyzers for analysis in real time of CO and $CO_2$ concentrations (fig. 6). The gas analyzers were calibrated periodically before, during, and after each test by using certified calibration gases traceable to National Institute of Standards and Technology reference gases.

**Temperature of the combustion gases**—The temperature of the combustion gases near each package was measured by using chromel-alumel thermocouples. The thermocouples in each package were referenced to 0 °C by electronic ice-point reference junctions, and an analog voltage (millivolt [mV] dc) was transmitted through an electrical umbilical to the ground station (fig. 7). The test area ambient temperature was measured similarly.

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[5] The use of trade and firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

**Velocity of the vertical component**—The velocity of the vertical component of the combustion gases (convection column) was measured in real time at each package location. Electronic vane anemometers were installed in packages 1, 3, and 5. Mass flow sensors were installed in packages 2 and 4. The mass flow sensors were temperature-compensated thermal anemometers having much lower startup threshold limits than the vane anemometers for sensing low velocities. Each velocity sensor transmitted an analog voltage through the electrical umbilical to the ground station (fig. 7). All velocity sensing instruments were calibrated in a wind tunnel with a reference standard anemometer before sampling.

**Data acquisition and control**—A data acquisition and control system (data logger) at the ground station was used to manage each of the sensor analog outputs, system status, scanivalve control, and real time data recording (fig. 7). The data logger performed three primary functions for the duration of each test: (1) interrogating each of the sensors and instruments on two-second intervals; (2) performing analog-to-digital conversions and math procedures; and (3) recording the data with time-stamp information on magnetic tape. The status of any input or output channel could be monitored, printed, or plotted at any time. In addition, the data logger controlled the scanivalve activation to obtain sequential gas samples from each of the sample packages on 25-second intervals for real-time CO and $CO_2$ analyses.

## Calculated Parameters

Gas and particulate matter concentrations were measured on volume-to-volume and mass-to-volume bases, respectively. The following parameters were calculated from concentration and mass flux data:

**1.** Emission factors ($EF_n$) for each emission (n).

**2.** Carbon flux and rate of fuel consumption.

**3.** Cumulative (integrated) carbon production and consumption of fuels.

**4.** Fire intensity (rate of heat release per unit area).

**5.** Combustion efficiency.

A detailed presentation of the calculation of these parameters is presented in appendix 2. The following description summarizes the carbon mass-balance derivations.

The carbon mass-balance method was used to assess the mass of fuel consumed that produced the emissions. The carbon mass-balance method accounts for the carbon released from the fuel during combustion by measuring the concentrations of the carbon-bearing combustion products. The carbon in the fuel is about 50 percent of the dry-weight mass of the fuel. The measured carbon contained in the combustion products is multiplied by two to calculate the mass of fuel consumed in producing the measured combustion products. Emission factors for specific emission components are then calculated by dividing the mass of the emission by the fuel consumed and are expressed in units of pounds of emission per ton of fuel consumed.

Concentrations of the predominant carbon species ($CO_2$, CO) were measured in real time. When coupled with concurrent real-time measurements of vertical velocity (and subsequent calculations of mass flux), carbon flux can be calculated for any point in time and can be integrated to represent the total flux of carbon for a specified period when concurrent grab sampling occurred. When divided by one-half—the proportionate mass of carbon to mass of fuel—these data are converted to rate of fuel consumption and integrated fuel consumption.

Emission factors presented here as averages for an entire fire (or fuel type) are referred to as "fire-average," and are means calculated by using a weighted-average procedure. The emission factors for a given phase (or for a given fire) are weighted by the total fuel consumed as determined through the real-time carbon-flux measurements (see appendix 2). The weighting procedure accounts for differences in both available fuel and fire processes among the respective phases or fuel types. Additionally, the procedure accounts for uneven sample sizes where data for a particular phase or fire were not complete.

## Statistical Procedures

### Biomass Data

Biomass data were analyzed statistically to quantify differences in fuel characteristics among the test sites. One-way analysis of variance (ANOVA) was used to test for differences among sites in total fuel loading, attached dead wood, standing dead stemwood, total dead fuel, and dead fuel fraction. If the null hypothesis that the mean of a given fuel parameter did not differ among sites was rejected at $\alpha = 0.05$, then Tukey's multiple comparison procedure was used to make pairwise comparisons among sites. The assumption of normal distribution of errors was tested by calculating the Shapiro-Wilk statistic from the residuals of each ANOVA. In no case was the null hypothesis, that the data were sampled from a normally distributed population, rejected at $\alpha = 0.05$.

Differences among sites in percentage of fuel consumed were evaluated by using the procedures outlined above for preburn fuel variables.

### Emissions Data

One-way ANOVA was used to test for differences among treatments in the emission factors of PM, PM2.5, PM10, CO, $CO_2$, $CH_4$, and NMHC. Separate tests were performed for flaming phase, smoldering phase, and overall fire. These ANOVAs were followed by contrasts to test a priori comparisons among specific treatments. Pairwise comparisons were made between the standing fuel units (Bear Creek, Newhall standing, TNC) to test the hypotheses that emission factors would differ among sites. The Newhall standing units were compared with the Newhall crushed units to test the hypothesis that crushing the chaparral into a more compact fuel bed results in different emission factors than burning standing chaparral. The Newhall crushed units were not compared to either of the other sites because it would not be possible to separate the effects of different fuel types and the crushing treatment.

Because only one unit was successfully burned at the TNC site, only one replicate was available from this site. The only way to test for differences between TNC and the other two sites would be to assume that the variance within the TNC site could be estimated by the pooled sample variance. This assumption may be valid if there is no evidence of heterogeneity of variance among the burning treatments for which

replicates were available. We tested the assumption of variance homogeneity among the Bear Creek site and the standing and crushed units at Newhall for each emission factor. Evidence of heterogeneity of variance at $\alpha = 0.05$ was found for smoldering phase PM10 and for smoldering phase and total fire for NMHC. For all other emission factors and phases, we cannot reject variance homogeneity. Therefore, homogeneity of variance was assumed, and the reader is reminded that all comparisons of emission factors involving the TNC site rely on this assumption. Further justification for making this assumption and including TNC in comparisons include the difficulty and expense of measuring emission factors, and the paucity of published data on emissions from prescribed burning of chaparral fuels.

The assumption of normal distribution of errors for each emission factor was tested by calculating the Shapiro-Wilk statistic from the residuals of each ANOVA. There were a few instances where evidence of nonnormality was encountered: these are indicated in "Results."

Linear regression analysis was used to examine the relation between reaction intensity and dead fuel fraction during flaming combustion for the standing fuel treatments. Regression analysis also was used to relate CO and $CH_4$ emission factors from both flaming and smoldering combustion to combustion efficiency.

## Results

### Execution of Tests

Four TNC tests were conducted on January 9 and 10, 1990. Ignitions of TNC1 and TNC2 were attempted on January 9. A malfunctioning "Terra-Torch" ignition device resulted in unacceptably low flame lengths and fire intensities as well as contamination of the samples by diesel fumes from the ignition device. A reburn of TNC1, named TNC3, was attempted on January 10 but met with similar results. TNC4 was successfully executed on January 10, 1990, and comprises the only valid data set from the TNC test area.

The three Newhall crushed unit tests were conducted between June 7 and 9, 1990. NEW1 and NEW2 were burned on June 7, 1990. The NEW6 test was completed on June 9, 1990.

Three Newhall test units were comprised of standing fuel (NEW3, NEW4, NEW5). NEW3 and NEW4 were burned on June 8, and NEW5 was burned on June 9, 1990.

The Bear Creek burns were conducted between June 19 and June 21, 1990. The BC1 and BC2 burns were conducted on June 19. No postburn biomass data were collected for BC1. The BC3 burn was ignited on June 21, 1990. This burn initially failed to ignite, and data recording was eventually stopped 22 minutes later. A new attempt to start the fire was made and the ignition strategy was successful in getting fire under the sampling packages. The new burn was called BC3.2. BC3.2 had more flame under the sampling packages and, therefore, was considered to be a single flaming phase with no smolder. BC3, on the other hand, had almost no flame under the packages, but did have combustion indicative of a smolder phase. Therefore, the data for these burns were recombined in the tables so that BC3 appears to be a complete burn (BC3.2 data as the flaming phase and BC3 as the smolder).

## Biomass

**Preburn biomass**—-Estimates of the preburn fuel loading and dead fuel fraction are presented by species and for each site in table 2. No biomass data are available for the Newhall crushed units, which were crushed before a fuels inventory could be made. Chamise was the dominant chaparral species on the Newhall and TNC sites, and the Bear Creek site was dominated by ceanothus. Total biomass on the Bear Creek site was nearly three times higher than on either Newhall standing or TNC. This difference, denoted by the capital letters "A" and "B" in table 2, is statistically significant ($\alpha$ = 0.05). Several other significant differences also are noted in table 2. Bear Creek had over four times more attached dead biomass than TNC, while TNC had nearly twice as much standing dead as Newhall (dead shrub boles from a 1980 fire remained on TNC). The fraction of dead biomass was significantly lower on Bear Creek than on Newhall standing or TNC ($\alpha$ = 0.05; table 2).

**Biomass consumption**—Total preburn fuel loadings, fuel consumption, and fraction of biomass consumed are presented in table 3 for each of the three sites (the Newhall crushed test plots are not included in these data). The fraction of preburn fuel consumed for the three sites ranged from 0.75 to 0.83. The fraction consumed did not differ among sites.

**Table 2—Estimates of total fuel loading and dead fuel loading, by species and sites, for all test sites prior to burning**

| Site and species[a] | Total biomass | Attached dead | Standing dead | Total dead | Fraction dead |
|---|---|---|---|---|---|
| | | | *Tons/acre*[b] | | |
| Bear Creek: | | | | | |
| ADFA | 3.4 ± 1.2 | 0.6 ± 0.2 | 0.7 ± 0.2 | 1.3 ± 0.4 | 0.41 ± 0.05 |
| CECR | 19.9 ± 2.4 | 2.7 ± 0.3 | 1.3 ± 0.5 | 3.9 ± 0.6 | 0.20 ± 0.02 |
| Total | 23.2 ± 1.6 ***A*** | 3.4 ± 0.3 ***A*** | 1.9 ± 0.5 ***AB*** | 5.2 ± 0.3 ***A*** | 0.23 ± 0.02 ***A*** |
| Newhall: | | | | | |
| ADFA | 7.9 ± 2.7 | 1.6 ± 0.6 | 0.9 ± 0.1 | 2.5 ± 0.7 | 0.35 ± 0.04 |
| Total | 7.9 ± 2.7 ***B*** | 1.6 ± 0.6 ***AB*** | 0.9 ± 0.1 ***B*** | 2.5 ± 0.7 ***B*** | 0.35 ± 0.04 ***B*** |
| TNC: | | | | | |
| ADFA | 4.7 ± 0.9 | 0.7 ± 0.2 | 1.7 ± 0.2 | 2.4 ± 0.4 | 0.52 ± 0.02 |
| QUBE | 2.5 ± 1.1 | 0.1 ± 0.0 | 0.9 ± 0.4 | 0.9 ± 0.4 | 0.42 ± 0.04 |
| RHIL | 0.2 ± 0.1 | 0.0 ± 0.0 | 0.0 ± 0.0 | 0.0 ± 0.0 | 0.14 ± 0.05 |
| Total | 7.3 ± 0.6 ***B*** | 0.8 ± 0.1 ***B*** | 2.6 ± 0.2 ***A*** | 3.4 ± 0.2 ***AB*** | 0.46 ± 0.01 ***B*** |

[a] Species identification: ADFA = *Adenostoma fasciculatum* (chamise); CECR = *Ceanothus crassifolius* (ceanothus); QUBE = *Quercus berberidifolia* (scrub oak); RHIL = *Rhamnus ilicifolia* (holly-leaf redberry).
[b] Values are means (± one standard error) of three 40-$m^2$ plots per site. The Newhall data represent the standing fuel units only. Within each column, differences among the site totals are indicated by the capital letters, where site totals sharing the same letter are not significantly different; $\alpha$ = 0.05 (one-way ANOVA followed by Tukey's test).

**Table 3—Total prefire fuel loading, fuel consumed by fire, and fuel consumption as a fraction of prefire fuel[a]**

| Site | Prefire total | Consumption | Fraction consumed |
|---|---|---|---|
| | *– – – Tons/acre – – –* | | |
| Bear Creek | 24.1 ± 2.4 | 20.2 ± 3.4 | 0.83 ± 0.06 |
| Newhall | 7.9 ± 2.7 | 6.0 ± 2.2 | 0.75 ± 0.04 |
| TNC | 8.6 | 6.6 | 0.77 |

[a] Values are means (± 1 standard error) of 2 burns at BC, 1 burn at TNC, and the 3 standing fuel burns at Newhall.

**Table 4—Average pooled plume temperature data and maximum and minimum values from the test units, by phase[a]**

| Phase | Statistic | Test area | | | |
|---|---|---|---|---|---|
| | | TNC | Newhall standing | Newhall crushed | Bear Creek |
| | | – – – – – – – – – – °C – – – – – – – – – – | | | |
| Flaming | Mean | 77.49 | 73.49 | 77.49 | 38.17 |
| | Stand. dev. | 35.11 | 18.43 | 60.51 | 9.73 |
| | Maximum | 206.10 | 144.70 | 166.90 | 118.40 |
| | Minimum | 43.20 | 41.80 | 45.30 | 29.00 |
| Smolder | Mean | NA | 52.53 | 60.51 | 39.32 |
| | Stand. dev. | NA | 6.90 | 13.10 | 12.50 |
| | Maximum | NA | 78.00 | 107.30 | 107.10 |
| | Minimum | NA | 36.90 | 36.20 | 27.60 |

NA = not available.
[a] The data are pooled from observations recorded by all five sampling packages for all tests.

## Temperature, Velocity, and Flux Data

**Plume temperature**—Pooled plume temperature data for each burn type are shown in table 4. These data represent the mean values from all tests within a respective treatment.

Flaming and smolder phase temperatures were lower for the Bear Creek burns than the other test burn units. Newhall crushed units showed greater variation in measured plume temperatures than the other test units; Bear Creek showed the least variation for flaming phase combustion and Newhall standing the least variation for smolder phase combustion.

**Table 5—Average pooled plume velocity data and maximum and minimum values from the test units, by phase[a]**

| Phase | Statistic | Test area | | | |
|---|---|---|---|---|---|
| | | TNC | Newhall standing | Newhall crushed | Bear Creek |
| | | *Meters per second* | | | |
| Flaming | Mean | 1.25 | 2.30 | 1.59 | 1.60 |
| | Stand. dev. | .44 | 1.57 | .85 | .79 |
| | Maximum | 2.90 | 8.10 | 5.90 | 6.50 |
| | Minimum | .30 | .30 | .30 | .30 |
| Smolder | Mean | NA | 1.43 | 1.64 | 1.68 |
| | Stand. dev. | NA | .54 | .50 | .76 |
| | Maximum | NA | 4.20 | 3.80 | 5.00 |
| | Minimum | NA | .60 | .70 | .40 |

NA = not available.
[a] The data are pooled from observations recorded by all five sampling packages for all tests.

**Table 6—Statistics for the mean rates of fuel consumption, by phase**

| Phase | Statistic | Test area | | | |
|---|---|---|---|---|---|
| | | TNC[a] | Newhall standing | Newhall crushed | Bear Creek |
| | | *Grams per square meter per second* | | | |
| Flaming | Mean | 1.28 | 7.32 | 3.17 | 0.97 |
| | Stand. dev. | NA | 5.00 | 2.46 | .75 |
| | Maximum | 2.35 | 15.10 | 10.16 | 2.71 |
| | Minimum | .75 | .61 | .46 | .08 |
| Smolder | Mean | NA | 1.56 | 1.98 | 1.40 |
| | Stand. dev. | NA | .98 | 1.03 | 1.00 |
| | Maximum | NA | 5.88 | 4.61 | 4.80 |
| | Minimum | NA | .32 | .11 | .18 |
| Fire | Mean | 1.28 | 3.62 | 2.64 | 1.27 |
| | Stand. dev. | NA | 4.09 | 1.94 | .95 |
| | Maximum | 2.35 | 15.10 | 10.16 | 4.80 |
| | Minimum | .75 | .30 | .11 | .08 |

NA = not available.
[a] Only 1 burn was recorded for TNC and it was entirely flaming phase.

**Plume velocity**—Pooled plume velocity statistics for each burn type are shown in table 5. These data are means from the replicate tests in each respective treatment.

Flaming plume velocities were highest at Newhall standing and lowest at TNC. Newhall standing also had the greatest variation in flaming plume velocity. Bear Creek had the greatest smolder phase plume velocity and also the greatest variation.

**Calculated parameters**—The rate of fuel consumption for each test within a treatment is plotted in figures 8, 9, 10, and 11 for Newhall Standing, Bear Creek, Newhall Crushed, and TNC, respectively. The plots provide an opportunity to compare the relative differences in fuel consumption among the replicate tests for a given treatment. Mean rate of fuel consumption statistics for the four test areas are contained in table 6. The mean values represent averages over the period for each phase of combustion.[6]

Newhall standing (fig. 8) had the greatest mean rate of fuel combustion and the greatest variation during the flaming phase, ranging from 0.61 to 15.10 $g/m^2 \cdot sec^{-1}$; Bear Creek (fig. 9) had the least in both categories (table 6). For the smolder phase, Newhall crushed (fig. 10) had the greatest rate of fuel combustion and also the greatest variation. Bear Creek had the lowest rate of fuel combustion, but Newhall standing had the lowest variance. For fire average data, Newhall standing had both the greatest rate of fuel combustion and variation and Bear Creek had the least.

Calculations of combustion efficiency are contained in table 7. For the flaming stage, Newhall crushed had the greatest combustion efficiency. Bear Creek had the least efficient burn during the flaming phase. Variation was highest on Newhall standing and lowest for Bear Creek. For the smolder phase, Bear Creek had the highest efficiency calculated and Newhall standing the lowest. Variation was highest for Newhall standing and lowest for Newhall crushed. For fire average data, TNC had the highest efficiency rating, but this is just using flaming phase data. Newhall crushed had the highest average efficiency rating. Bear Creek had the lowest and the smallest variance as well. The highest variation for fire average data was with Newhall standing.

Data for mean rate of heat release are shown in table 8. The highest mean rate of heat release during the flaming phase was for TNC. Bear Creek had the lowest value and the least variation for the flaming phase and also for the fire-average. The smolder phase rate of heat release for Bear Creek was the highest.

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[6] Periods for which the average values in tables 6, 7, and 8 were calculated are shown immediately below the x-axis of each plot in figures 8, 9, 10, and 11.

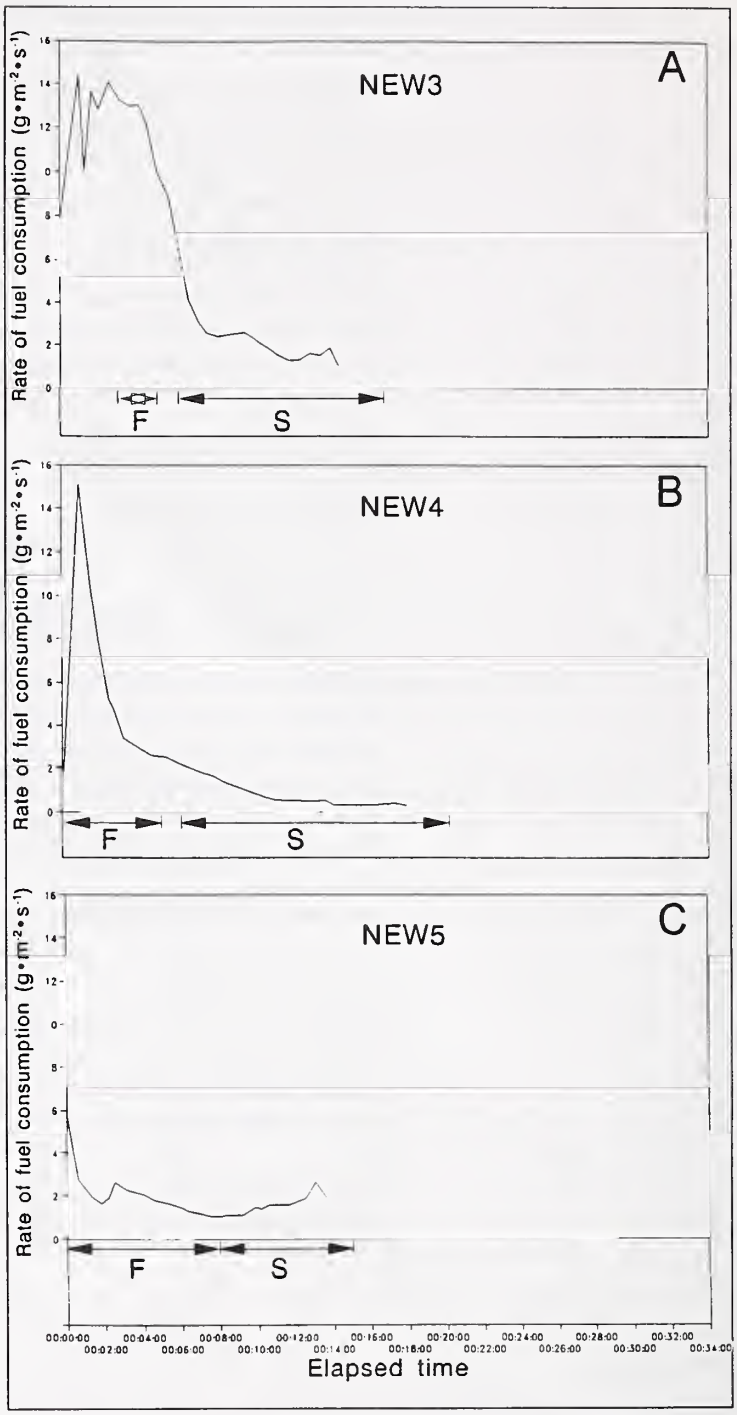


Figure 8—Fuel consumption rates for the three Newhall standing vegetation treatment tests: NEW3 (A), NEW4 (B), and NEW5 (C). The flaming (F) and smoldering (S) sampling periods are indicated below the horizontal arrows.

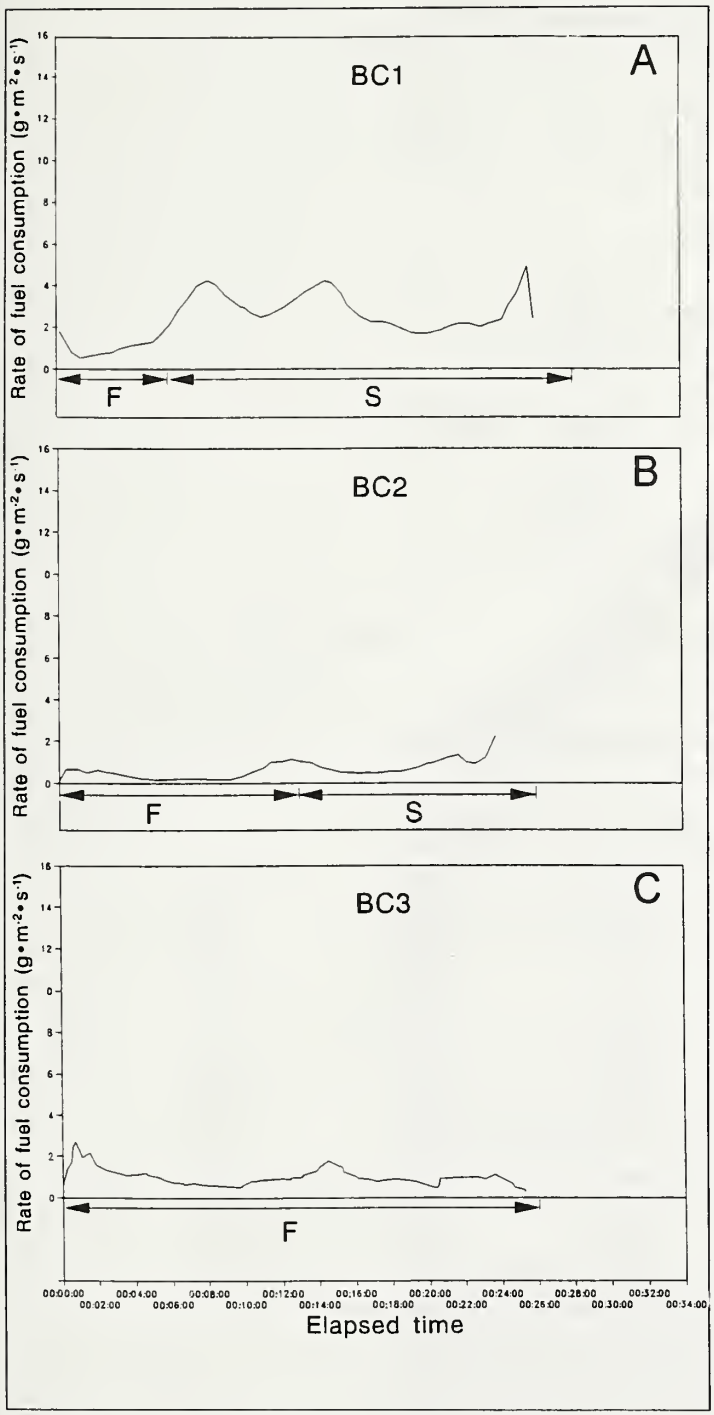


Figure 9—Fuel consumption rates for the three Bear Creek standing vegetation treatment tests: BC1 (A), BC2 (B), and BC3 (C). The flaming (F) and smoldering (S) sampling periods are indicated below the horizontal arrows

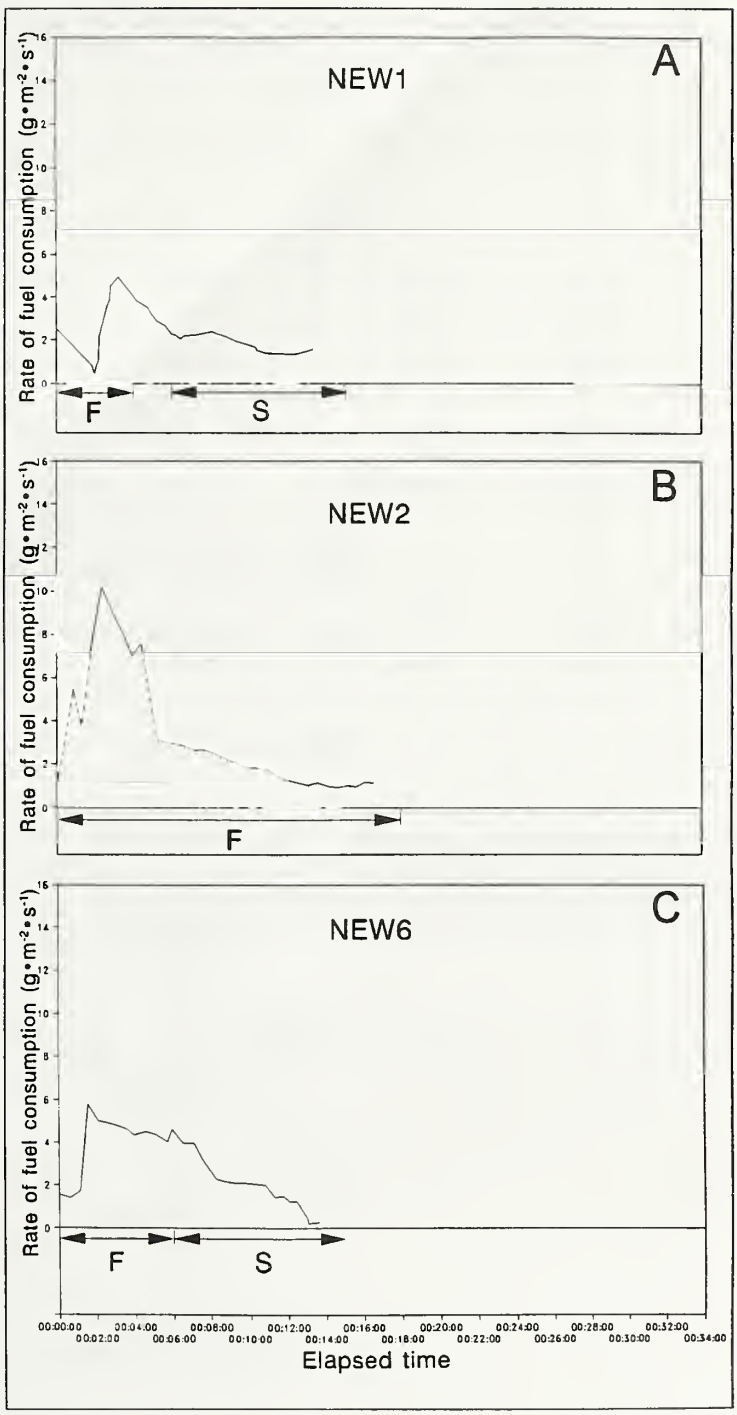


Figure 10—Fuel consumption rates for the three Newhall crushed vegetation treatment tests: NEW1 (A), NEW2 (B), and NEW6 (C). The flaming (F) and smoldering (S) sampling periods are indicated below the horizontal arrows.

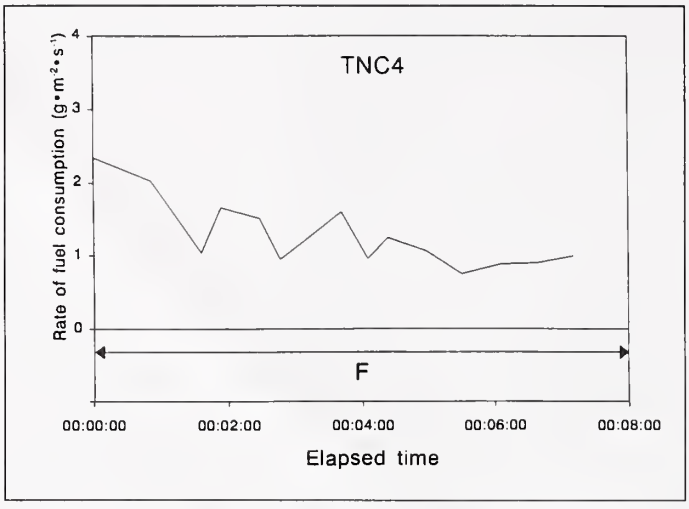


Figure 11—Fuel consumption rates for the standing vegetation treatment test at The Nature Conservancy (TNC4). The flaming (F) sampling period is indicated below the horizontal arrow.

**Table 7—Combustion efficiency statistics for the 4 treatment areas**

| Phase | Statistic | Test area | | | |
|---|---|---|---|---|---|
| | | TNC[a] | Newhall standing | Newhall crushed | Bear Creek |
| | | *Percent* | | | |
| Flaming | Mean | 90.10 | 91.48 | 93.68 | 89.82 |
| | Stand dev. | NA | 1.37 | 1.13 | .85 |
| | Maximum | 90.10 | 92.34 | 94.56 | 90.60 |
| | Minimum | 90.10 | 89.91 | 92.41 | 88.92 |
| Smolder | Mean | NA | 84.74 | 85.28 | 86.60 |
| | Stand dev. | NA | 1.58 | .63 | 1.35 |
| | Maximum | NA | 86.05 | 85.95 | 87.84 |
| | Minimum | NA | 82.99 | 84.69 | 85.16 |
| Fire | Mean | 90.10 | 87.29 | 87.62 | 87.23 |
| | Stand dev. | NA | 3.27 | 2.75 | 1.66 |
| | Maximum | 90.10 | 89.27 | 90.21 | 88.47 |
| | Minimum | 90.10 | 83.52 | 84.73 | 85.34 |

NA = not available.
[a] Only 1 burn was recorded for TNC and it was entirely flaming phase.

**Table 8—Statistics for the rate of heat release for the 4 treatment areas**

| Phase | Statistic | Test area | | | |
|---|---|---|---|---|---|
| | | TNC[a] | Newhall standing | Newhall crushed | Bear Creek |
| | | *Kilowatts per square meter* | | | |
| Flaming | Mean | 175.51 | 149.60 | 80.55 | 19.33 |
| | Stand. dev. | NA | 100.17 | 48.67 | 11.55 |
| | Maximum | 175.51 | 261.51 | 125.31 | 31.51 |
| | Minimum | 175.51 | 68.32 | 28.74 | 8.53 |
| Smolder | Mean | NA | 114.14 | 91.60 | 127.63 |
| | Stand. dev. | NA | 101.56 | 73.46 | 102.48 |
| | Maximum | NA | 225.93 | 175.17 | 229.92 |
| | Minimum | NA | 27.57 | 37.23 | 24.97 |
| Fire | Mean | 175.51 | 127.97 | 85.56 | 81.83 |
| | Stand. dev. | NA | 70.00 | 61.57 | 49.43 |
| | Maximum | 175.51 | 189.15 | 155.35 | 114.63 |
| | Minimum | 175.51 | 51.64 | 38.93 | 24.97 |

NA = not available.
[a] Only 1 burn was recorded for TNC and it was entirely flaming phase.

## Emissions

Average emission factors for each of the four treatments are presented in table 9. The emission factors are means of the replicate tests within each treatment and are expressed as pounds of emission produced per ton of fuel consumed. The standard error of the mean (SE) is also presented for each emission factor. Smoldering emissions were not sampled on the TNC treatment; therefore, neither smoldering data nor SEs are presented for TNC.

**Differences among standing sites**—Several significant differences in emission factors were detected among the three standing vegetation treatment sites; Newhall standing, Bear Creek, and TNC.[7] For CO, the flaming emission factor was higher for TNC than for Newhall standing ($p=0.0393$).[8] The smoldering emission factor for CO was higher for Newhall standing than for Bear Creek ($p=0.0503$). The flaming phase NMHC emission factor for Bear Creek was over three times higher than both Newhall standing and TNC ($p=0.0071$ and $p=0.0293$, respectively).

[7] Recall that only one unit was successfully burned at TNC; therefore, all comparisons of emission factors involving TNC rely on the assumption of variance homogeneity as discussed in "Methods," except for smoldering phase PM10 and smoldering and fire-average NMHC, where the assumption was rejected by Bartlett's test for variance homogeneity.

[8] All references to "higher" or "lower" in this discussion imply significance.

**Table 9—Mean emission factors for each test area, by phase of combustion, expressed in units of pounds of emission per ton of fuel consumed with standard error of the mean (SE)**

| Treatment name | Phase[a] | Emission factors | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | PM | PM10[b] | PM2.5 | CO | $CO_2$[c] | $CH_4$ | NMHC |
| | | *Pounds per ton (±SE)* | | | | | | |
| Bear Creek | Flame | 37.6 ± 7.4 | 15.3 | 10.7 ± 1.4 | 110.9 ± 14.3 | 3296.5 ± 17.9 | 4.1 ± 1.0 | 37.2 ± 3.4 |
| | Smolder | 44.1 ± 6.3 | 23.7 | 19.5 ± 1.1 | 163.3 ± 29.2 | 3178.2 ± 28.7 | 8.7 ± 2.0 | 45.0 ± 18.2 |
| | Fire | 41.3 ± 6.5 | 21.3 | 17.2 ± 1.7 | 160.3 ± 28.4 | 3201.3 ± 35.3 | 8.0 ± 2.0 | 39.4 ± 13.5 |
| Newhall crushed | Flame | 19.7 ± 7.7 | 14.0 | 12.8 ± 5.1 | 65.6 ± 4.8 | 3438.2 ± 23.9 | 1.8 ± 0.1 | 3.7 ± 0.7 |
| | Smolder | 32.2 ± 6.5 | 25.8 | 24.5 ± 10.5 | 222.6 ± 4.2 | 3129.9 ± 13.4 | 10.8 ± 0.6 | 13.1 ± 1.3 |
| | Fire | 28.4 ± 7.9 | 23.4 | 22.4 ± 10.3 | 174.4 ± 20.7 | 3225.0 ± 50.5 | 7.9 ± 0.8 | 10.4 ± 1.0 |
| Newhall standing | Flame | 29.8 ± 5.3 | 15.5 | 12.5 ± 2.7 | 96.1 ± 8.0 | 3357.4 ± 29.0 | 2.2 ± 0.4 | 12.1 ± 6.9 |
| | Smolder | 35.9 ± 3.3 | 25.7 | 23.6 ± 8.0 | 231.0 ± 16.8 | 3110.0 ± 33.5 | 9.3 ± 1.8 | 16.2 ± 4.6 |
| | Fire | 32.6 ± 2.7 | 19.6 | 17.0 ± 4.3 | 181.4 ± 33.7 | 3203.6 ± 69.2 | 7.1 ± 2.5 | 13.2 ± 4.8 |
| TNC[d] | Flame | 25.4 | 16.9 | 15.2 | 147.8 | 3306.8 | 2.9 | 11.9 |
| | Smolder | NA | NA | NA | NA | NA | NA | NA |
| | Fire | 25.4 | 16.9 | 15.2 | 147.8 | 3306.8 | 2.9 | 11.9 |

NA = not available.
[a] Flame=flaming phase; smolder=smoldering phase; fire=fire-weighted averages.
[b] SE is not shown for PM10 because PM10 is derived, not measured.
[c] An emission factor for $CO_2$ can exceed the mass of the fuel consumed (>2,000 lb\ton) because of the additional mass of oxygen ($O_2$) brought into the combustion reaction.
[d] Only 1 observation was made for TNC; therefore, SE is not shown for that treatment.

**Newhall standing vs. Newhall crushed**—The hypothesis that crushing the chaparral would result in significant differences in emission factors was tested using a priori comparisons of the Newhall crushed and Newhall standing treatments (previous data and experience support the use of 1-tailed comparisons for certain emission variables). For the flaming combustion phase, both CO and $CO_2$ emission factors were significantly different between Newhall crushed and Newhall standing. The CO emission factor for Newhall standing was higher ($p=0.0151$), and the $CO_2$ emission factor for Newhall crushed was higher ($p=0.0488$). Because combustion efficiency is derived from the $CO_2$ emission factor, the flaming phase combustion efficiency was also higher for Newhall crushed ($p=0.0489$).

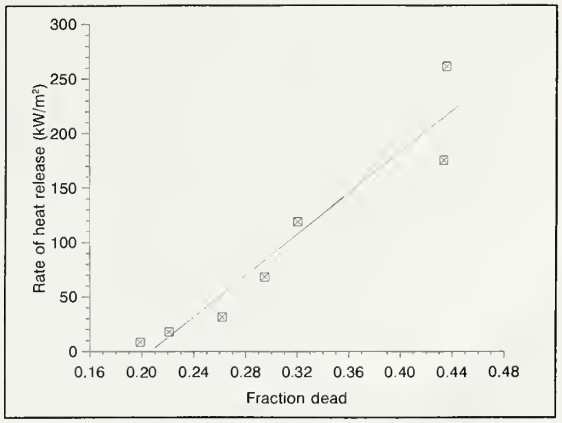


Figure 12—The rate of heat release plotted as a function of fraction dead (FRDEAD) for all standing vegetation tests, flaming phase. (Rate of heat release = FRDEAD • 943.56 - 194.74; $R^2$ = 0.91).

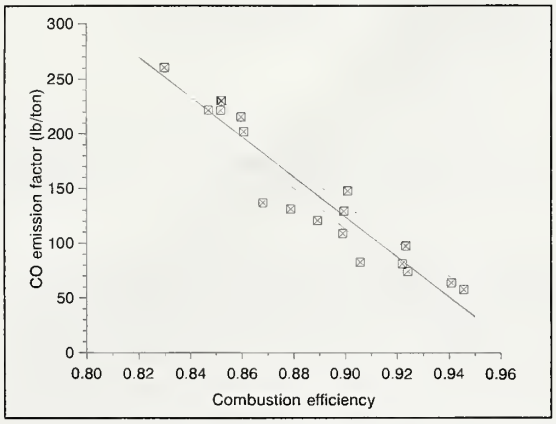


Figure 13—Emission factor for CO plotted as a function of combustion efficiency (CE) for all tests, flaming and smoldering phases. ($EF_{CO}$ = 1765.81 - CE • 1824.00; $R^2$= 0.91).

## Relations—Data and Discussion

Linear regression analyses detected several significant relations between emissions variables and observed or estimated fuel parameters ($\alpha$=0.05).[9] Figures 12, 13, and 14 each contain the observed data, regression lines, and the upper and lower 95-percent confidence limits.

For the flaming combustion phase on the standing treatment sites, the rate of heat release is strongly related to the fraction of dead biomass ($R^2$ = 0.91). This relation is plotted in figure 12. Although the two observations with the highest fraction dead are considerably far removed from the rest of the data, eliminating them from the model would not significantly affect the slope of the regression. Note that the regression for this relation does not intercept the origin. The model indicates that under the fire and fuel conditions represented in this study some fraction (> about 20 percent) of dead material was necessary to sustain combustion. This relation is clearly limited to the flaming phase, because all or most of the dead fraction of the available biomass is consumed in flaming combustion.

When the data from both combustion phases for all four treatment sites are combined, both CO and $CH_4$ emission factors exhibit strong, negative correlations with combustion efficiency. The observed CO emission factors are plotted with the

[9] Significance in these regressions does not necessarily imply causation, but certain relations do exhibit behavior that is both physically explainable and previously documented in other research.

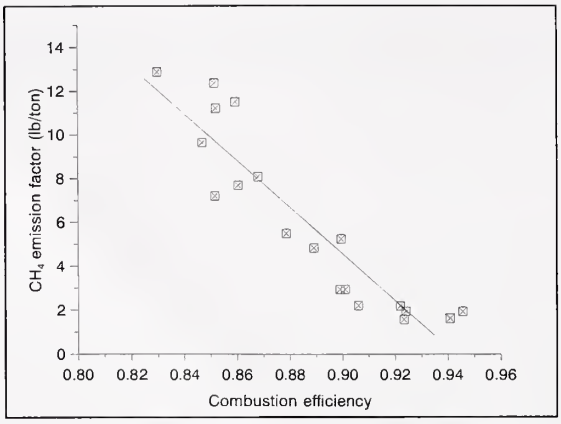


Figure 14—Emission factor for CH4 plotted as a function of combustion efficiency (CE) for all tests, flaming and smoldering phases. (EFCH4 = 100.62 - CE * 106.71; $R^2$ = 0.85).

CO combustion efficiency regression ($R^2$ = 0.91) in figure 13. Figure 14 is the plot of observed $CH_4$ emission factors and the $CH_4$ combustion efficiency regression ($R^2$ = 0.85).

## Comparisons With Previous Studies

### Emission Factors

Smoke emissions from chaparral fires have been sampled at various scales, from laboratory combustion experiments to airborne sampling of full-scale wildfires. Examples of these data include a burning table and combustion hood experiment by Weise and others (1991) and data from two separate airborne sampling efforts (Einfeld and others 1989, Radke and others 1991). The scale of our study of chaparral emissions was somewhere between these scales, and the data can be compared with several data sets from these other research approaches.

Two of the four chaparral species sampled by Weise and others (1991), with a burning table and combustion hood approach, were chamise and ceanothus. Mean emission factors from the flaming phase tests in these two species were much higher than from our study. The mean CO emission factor from their tests was 273 lb/ton, compared with 119 lb/ton from our study; both the mean values and their coefficients of variation were more than double those from our study. The mean PM emission factor from the burning table tests of chamise and ceanothus was 90 lb/ton—nearly three times greater than the PM emission factor of 31.6 lb/ton from the standing chaparral data of our study.

In contrast to the burning table tests, data from the airborne sampling of chaparral are much more similar to the data from the present study. Radke and others (1991) report fire-average emission factors for CO and PM3.5 of 149 lb/ton and 29.8 lb/ton, respectively. The fire-average CO emission factor from our study was 171 lb/ton, and the PM2.5 emission factor was 17.1 lb/ton. Because the PM3.5 emission factor from Radke and others (1991) represents a larger fraction of total particulate matter than our study (PM3.5 vs. PM2.5, respectively), a somewhat higher emission factor is expected. Finally, Einfeld and others (1989) report a fire-average PM2.5 emission factor of 21.8 lb/ton—a difference of only 20 percent when compared to our study's PM2.5 emission factor of 17.1 lb/ton for standing chaparral. Hardy and others (1992) report similar agreement of emissions data in their comparison of data from another deployment of the same airborne sampling system with estimates from ground-based sampling system results.

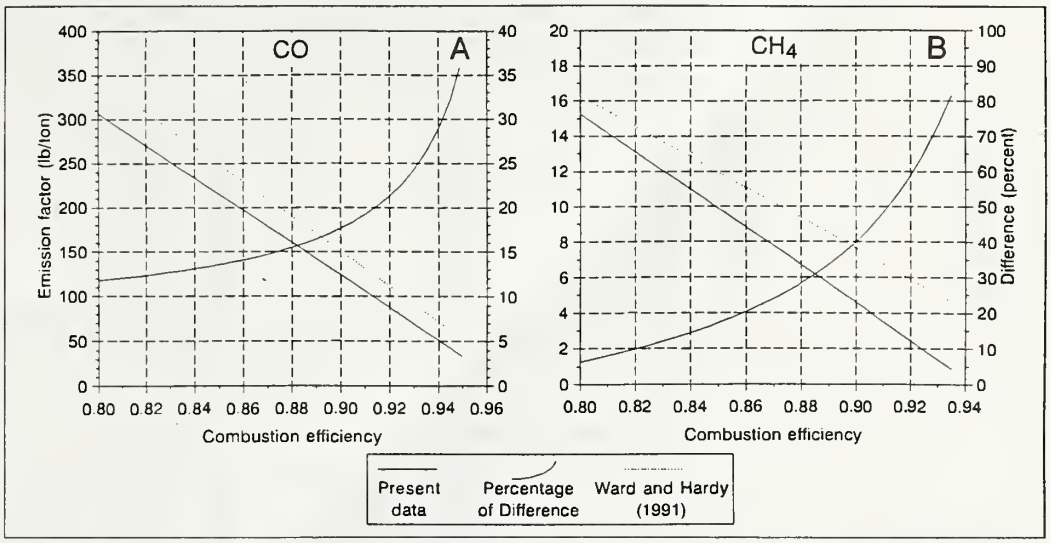


Figure 15—Comparison of regressions from the present study (solid, straight lines) and the 1991 equations from Ward and Hardy (1991; dotted lines) for predicting CO emission factor (A) and $CH_4$ emission factor (B) from combustion efficiency. The Y-axis at the right is percentage of difference between the two equations ([$eq._{1991}$-$eq._{present}$] over $eq._{1991}$) and is represented by the curves.

**Combustion Efficiency**

The strength of the relations between emissions and combustion efficiency (see "Relations—Data and Discussion") has been demonstrated in previous studies and is now becoming the basis for the modeling of numerous emissions components. Ward and Hardy (1991) present linear regression models based on combustion efficiency for estimating CO, $CO_2$, PM, PM2.5, and $CH_4$. Their models were developed from tests in six different fuel types and have been applied to local as well as global projections of emission from biomass burning (Ward and Hao 1991, Ward and others 1993). The regression equations developed from the present data are somewhat different from the equations of Ward and Hardy (1991).[10] These differences are shown in figure 15 for CO (A) and $CH_4$ (B). The straight, solid lines are reproduced from figures 13 and 14 for CO and $CH_4$, respectively, and the dashed lines represent the 1991 equations. The slopes appear to be relatively similar, but the percentage of difference shown by the curved line increases (in both cases) with higher combustion efficiencies. An example of the implications of the differences in the regressions can be made by estimating emission factors from the fire-average combustion efficiency for the Newhall Crushed treatment—a value of 0.92 (table 7). An emission factor for CO estimated from the present regression would be 87 lb/ton, and the 1991 regression would produce an emission factor for CO of 112 lb/ton—a difference of 22 percent. The difference in estimates of $CH_4$ are more dramatic: the present regression predicts an emission factor for $CH_4$ of 2.4 lb/ton, and the 1991 regression predicts a value of 5.9 lb/ton—a difference of 60 percent.

[10] These equations hereafter are referred to as the "1991 equations."

**Table 10—Mean emission factors, by phase, for all standing chaparral burns combined, including the 7 tests from the present study (NH3, NH4, NH5, BC1, BC2, BC3, TNC4) and 2 Lodi tests (Lodi1 and Lodi2)[a]**

| Phase | Weighted-average emission factors[b] | | | | | | |
|---|---|---|---|---|---|---|---|
| | PM | PM10[c] | PM2.5 | CO | $CO_2$ | $CH_4$ | NMHC |
| | *Pounds per ton (±SE)* | | | | | | |
| Flaming | 31.6 ± 2.6 | 16.5 | 13.5 ± 1.1 | 119.2 ± 10.9 | 3326.2 ± 14.6 | 3.4 ± 0.5 | 17.2 ± 6.8 |
| Smolder | 40.0 ± 4.1 | 24.7 | 21.6 ± 2.1 | 197.2 ± 33.9 | 3144.1 ± 34.1 | 9.0 ± 0.3 | 30.6 ± 14.4 |
| Fire | 34.1 ± 3.7 | 20.1 | 17.3 ± 1.2 | 153.7 ± 13.6 | 3257.9 ± 39.7 | 5.7 ± 1.2 | 19.6 ± 8.3 |

[a] Ward and Hardy (1989).
[b] Standard error of the mean (SE) is given for each emission factor.
[c] SE is not shown for PM10 because PM10 is derived, not measured.

## Combined Surface-Based Emissions Data

Prior to the present research, the only existing surface-based, in situ measurements of emissions from prescribed burning of chaparral were those from the 1987 Lodi tests (Ward and Hardy 1989). The sampling design and measurement protocols in our study closely follow that work. Our evaluation of the vegetation and fire parameters for the three Lodi tests indicated that two of the Lodi tests (called Lodi1 and Lodi2) were quite similar to the standing chaparral tests of our study. We combined the results presented here for the standing chaparral tests with data from the two Lodi tests to produce a comprehensive set of emission factors for prescribed burning of standing chaparral in southern California. The emission factor data presented in table 10 represent the mean pooled values for all tests in standing chaparral, including the two Lodi tests.

Emission factors for $CH_4$, CO, PM2.5, and $CO_2$ from each of the five vegetation treatments (Newhall crushed, Newhall standing, Lodi, TNC, and Bear Creek) are presented with the mean pooled values (from standing treatments only—see table 10) in figure 16. The relative magnitude of the differences in emissions among treatments can readily be seen. It is also apparent from figure 16 that the emission factors from the Lodi tests (only flaming phase emissions were reported) lie within the range of the other data.

## Management Implications

The applied research effort reported here was conceived, designed, and executed to provide managers of southern California chaparral with answers to three questions:

**1.** What is the quantity and character of smoke emissions produced from prescribed burning of chaparral?

**2.** Do emissions differ substantially with differences in vegetation characteristics?

**3.** Can compaction through mechanical crushing mitigate or alter smoke emissions from chaparral burning?

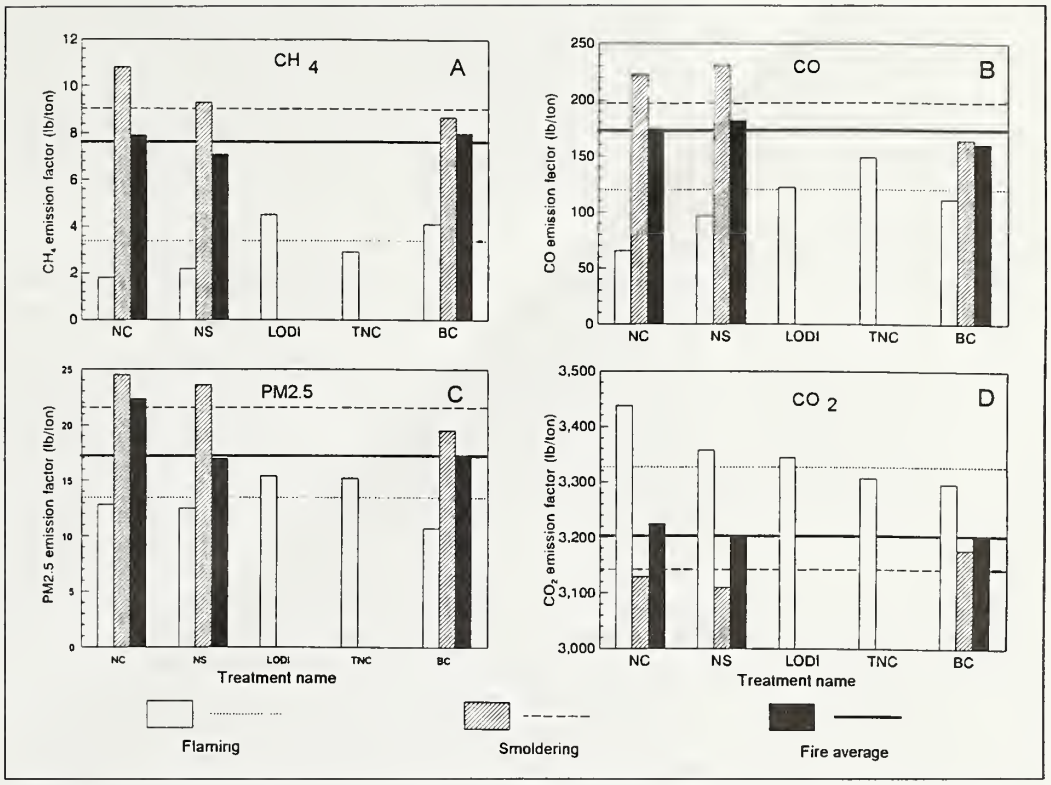


Figure 16—Flaming, smoldering, and fire-average emission factors for $CH_4$ (**A**), CO (**B**), PM2.5 (**C**), and $CO_2$ (**D**) for the four present study areas and two Lodi tests (Ward and Hardy 1989). The horizontal lines represent the average emission factors for all standing vegetation tests.

## Applying the Emission Factors

Smoke management personnel in southern California now have a comprehensive set of emission factors from a relatively large number of observations. The emission factor data presented in "Emissions" and "Combined Surface-Based Emissions Data" (above) can be used immediately by managers of both air and terrestrial resources. These data describe the mass of emissions expected to be produced from a given mass of consumed fuel. Additionally, they represent both flaming and smoldering consumption. The emission factor can be used to plan, monitor, and document the general impacts of a prescribed burning program on the air resource.

Emission factor data from similar research and of similar format have been distributed by the Environmental Protection Agency (EPA) in the compilation of emission factors (AP-42). Data from this study have been accepted by the EPA and are published in the current revision of AP-42 (U.S. EPA 1991). The data in AP-42 form the basis in many state smoke management programs for permits, daily ignition scheduling, fee structures, and impact analyses. The present data can facilitate such programs in southern California.

Few significant differences in emissions were detected among the four treatment regimes examined here; this may be due mainly to inadequate replication (lack of power) to detect what might be significant differences for the purposes of management decisionmaking. We recommend that the emission factors presented here for a particular treatment regime be applied cautiously, with the knowledge that site and environmental differences may cause substantial deviations from specific emission factors presented here.

For estimating emissions in planning prescribed burns, we recommend use of the average emission factors presented for all the fires we have measured in standing chaparral. Although these may differ somewhat from true emission factors for any individual fire, they provide the best estimate currently available. In our study, fuel characteristics such as species composition, fuel loading, and dead fuel fraction differed among sites, as did weather conditions and fire behavior. With so many factors that could influence emission factors changing simultaneously, our study unfortunately does not elucidate how each one affects emissions. Many burn experiments would need to be conducted with a design calling for carefully controlled and replicated burning conditions and stand characteristics. Furthermore, other sources of error in estimating total emissions from a specific fire are likely to be just as large as any error introduced by not having more site-specific emission factors. For example, accurate measurements of fuel loading are rarely available, because of the time and expense required to obtain them. So it is typical to use estimates based on averages or typical values for similar types of vegetation. However, few data of this nature are available, and fuel loadings on sites even of similar composition and age can differ greatly (Conard and Regelbrugge 1993, Paysen and Cohen 1990). Estimating fuel consumption in a given fire is another source of error. We measured values ranging from 75 to 83 percent (table 3) in this study, but few data are available from other studies for comparison. Riggan and others (1994) estimate that 60 percent of the wood less than 0.5 cm in diameter was consumed in a fire in 22-year-old ceanothus, considerably less than the 83-percent consumption we observed at Bear Creek. Because of these other potential sources of error, we see little reason for concern about using average values for emission factors rather than more stand or site-specific data, particularly because the basis for determining site-specific emission factors is weak. In fact, the site-to-site variation among particulate emission factors is likely to be considerably less than variation in fuel loading or in fuel consumption.

The emission factors reported here for PM10 must be applied with caution. PM10 was not measured in this study. Rather, it was derived from a PM-PM2.5 ratio developed by Radke and others (1990) from tests including smoke emissions from fires in vegetation types other than chaparral. We have not determined a chaparral-specific ratio.

**Mitigation of Smoke Emissions**

The inadequate replication within each treatment may have precluded detection of many significant differences in emissions among treatments, but the results from this study nonetheless provided new information on the relative effects of different treatment regimes on emissions production. These differences, although not necessarily statistically significant, may be relevant to programmatic planning of fuel treatment options and smoke mitigation strategies.

**Alternative treatment regimes**—These results suggest positive smoke management implications for crushing. For example, the highest combustion efficiencies observed for the flaming phase were from the Newhall crushed tests. The flaming phase emission factors for PM, PM10, CO, $CH_4$, and NMHC from Newhall crushed tests were lower than for any of the other areas. The flaming phase CO emission factor was significantly lower for Newhall crushed than for the Newhall standing tests, and the $CO_2$ emission factor was significantly lower (lower combustion efficiency) for Newhall standing than for Newhall crushed. The data also showed that flaming phase (the predominant phase) $CH_4$ and NMHC emissions from old ceanothus (Bear Creek) are higher than from any other test.

**Alternative prescription strategies**—The results from the regression analyses (see "Relations—Data and Discussion") demonstrate several strong relations between fire behavior and emissions production. These relations enhance the understanding of emissions production from various fuel and fire scenarios and provide new knowledge for future modeling efforts. Several of the relations, for example, $CH_4$ versus combustion efficiency, are relatively similar to those previously documented.

The management implications of several of the relations documented in our study are significant. The $CH_4$-combustion efficiency relation for all phases of the standing-fuel tests is an excellent example, where the emission factor for $CH_4$ is inversely related to combustion efficiency; an $R^2$ value of 0.85 shows the strength of the relation, based on 19 observations (fig. 14). Theoretically, a carefully executed prescription that increases combustion efficiency by 5 percent can reduce the $CH_4$ emission factor by as much as 50 percent.

## Conclusions

Emission factors for PM, PM2.5, PM10, CO, $CO_2$, $CH_4$, and NMHC have been developed from measurements of smoke emissions from 12 prescribed burns in southern California chaparral. Three replicate tests were performed in each of four distinct fuel and fire regimes common to vegetation management operations. The results represent smoke emissions from chaparral for a range of stand conditions.

The emission factors now form the most complete set of data available from which management decisions can be made on the impacts of prescribed burning on the air resource. The data set provides emission factors for each phase of combustion for each of the four fire and fuel regimes and also provides weighted-average values from the combined tests for general use in describing emissions from standing chaparral vegetation.

Combustion efficiency was calculated for each phase of combustion for each test. The rates of fuel consumption and heat release were derived from real time measurements of CO, $CO_2$, temperature, and vertical mass flux.

The results help provide new knowledge on the characteristics of the emissions and their relations to fuel and fire parameters. Specific results are summarized:

**1.** The flaming phase predominates for fuel consumption and emissions production.

**2.** The crushed treatment resulted in the lowest flaming phase emission factors for PM, PM10, CO, $CH_4$, and NMHC. The crushed treatment also had the highest mean combustion efficiency (93.68) for the flaming phase.

**3.** Flaming phase NMHC emission factor from old ceanothus (Bear Creek) was over three times higher than the same phase of any other standing treatment.

**4.** The differences among treatments for most other emission factors were not statistically significant and therefore are inconclusive for management options.

**5.** While the prefire fuel loadings differed significantly among sites, the fraction of fuel consumed (percentage consumed) did not differ significantly among standing treatments.

**6.** $CH_4$ emission factors are well correlated with combustion efficiency ($R_2$ value of 0.85).

**7.** Data from the previous Lodi tests are similar to, and can be combined with, the standing vegetation treatments from our study. When the data are pooled, emission factors can be presented that represent smoke emissions from standing chaparral vegetation in southern California.

**8.** Emission factors and combustion efficiencies from this study are similar to results from airborne sampling of smoke emissions from prescribed chaparral fires. Data from both this study and airborne studies differ considerably from results from burning table experiments.

The variances in data from in situ combustion experiments are great, making the development of causal relations difficult, at best. The variances observed from the present carefully administered tests demonstrate the degree of difficulty and concomitant high cost of such research. These and other relations must be further explored, and the data must be combined with data from other studies to develop better emission modeling capabilities.

## Acknowledgments

Many people and agencies independent of the sponsor (State of California, Department of Forestry and Fire Protection [CDF]) contributed to this effort. The planning and logistical support provided by Captain Scott Franklin (now retired) and the Los Angeles County Fire Department was exceptional.

One of the test areas was located in the Santa Rosa Plateau Preserve, owned and managed by The Nature Conservancy. We are indebted to The Nature Conservancy and manager Gary Bell for access to the preserve and especially for the gracious hospitality in housing our crew for over 2 weeks.

The personnel from the vegetation management program of CDF are clearly committed to the aggressive pursuit of new knowledge in support of their operations. We thank Jim Carter from the Riverside Unit and acknowledge the personal and professional commitment of the executive sponsor for this work, Dale Wierman.

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## Conversion Factors

| Parameter | Multiply this unit: | By this factor: | To obtain this unit: |
|---|---|---|---|
| **Biomass loading** | megagrams per hectare (Mg/ha) | 0.4461 | tons per acre (ton/acre) |
| | tons per acre (ton/acre) | 2.2417 | megagrams per hectare (Mg/ha) |
| **Emission factor** | grams per kilogram (g/kg) | 2.0 | pounds per ton (lb/ton) |
| | pounds per ton (lb/ton) | 0.5 | grams per kilogram (g/kg) |
| **Volume** | liters (l) | 0.03531 | cubic feet ($ft^3$) |
| | cubic feet ($ft^3$) | 28.3206 | liters (l) |
| **Flow rate** | liters per minute (l/min) | 15.852 | gallons per hour (gal/h) |
| | gallons per hour (gal/h) | 0.0631 | liters per minute (l/min) |
| **Length** | micrometers (µm) | 0.0000394 | inches (in) |
| | inches (in) | 25,400 | micrometers (µm) |
| | millimeters (mm) | 0.0394 | inches (in) |
| | inches (in) | 25.4000 | millimeters (mm) |
| | meters (m) | 3.2808 | feet (ft) |
| | feet (ft) | 0.3048 | meters(m) |
| **Area** | hectares (ha) | 2.471 | acres |
| | acres | 0.4047 | hectares (ha) |
| **Velocity** | meters per second (m/s) | 2.237 | miles per hour (mi/h) |
| | miles per hour (mi/h) | 0.477 | meters per second (m/s) |
| **Temperature** | degrees Celsius (°C) | [(°C*1.8)+32] | degrees Fahrenheit (°F) |
| | degrees Fahrenheit (°F) | [(°F–32)*0.555) | degrees Celsius (°C) |

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## Table 11—Specifications for instrumentation and apparatus

| Measurement parameter | Application: Grab | Application: Real | Sensor manufacturer and model | Measurement technique | Range (90% full scale) | Approximate accuracy (±) | Analog output[a] |
|---|---|---|---|---|---|---|---|
| Data acquisition | X | X | John Fluke Mfg. Co. Inc; model 2280A | Analog to digital input/output and control | N/A | 0.01% | N/A |
| Carbon monoxide | X | X | Horiba Instr. Inc; model PIR-2000 | Nondispersive infrared | 0-2000 ppm | 0.5% | 0-100 mV |
| Carbon dioxide | X | X | Horiba Instr. Inc; model PIR-200 | Nondispersive infrared | 0-5000 ppm | 0.5% | 0-100 mV |
| Nitrous oxide | X | X | Horiba Instr. Inc.; [custom] | Nondispersive infrared | 0-100 ppm | 0.5% | 0-100 mV |
| $CH_4$ and NMHC | X | | Baseline Ind., Inc.; model P1030A | Gas chromatography | N/A | 2.0% | 0-100 mV |
| Vertical mass flow (2,4) | | X | Kurz Inst. Inc.; model 450-DC-SP-HTT | Temperature-compensated thermal anemometer | 0-15 m/s | 0.25% | 0-5 Vdc |
| Vertical airspeed (1,3,5) | | X | Qualimetrics; model 24201 | Vane anemometer | 0-10 m/s | 3.00% | 0-30 Vac |
| Temperature | | X | Chromel-alumel with Omega Engineering Inc. electronic ice point; model MCJ-K | Thermocouple | 0-1250 C | 1.00 C | 0-50 mV |
| Electro-balance | X | | Cahn Instr. Inc.; model 28 | Closed loop electro-mechanical | A.200 mg<br>B.1000 mg | 1.00 µg<br>10.00 µg | Digital display |
| Vacuum pump for 7 l/min, 47-mm filters | X | | Gast Mfg. Corp; model 3040V-29B | Rotary carbon vane vacuum pump | 35 l/min at 25 in mercury | Volume through each filter regulated by critical-flow orifice | N/A |
| Vacuum pump for each 2-l/min, 37-mm filter and gas analyzers | X | X | ASF Inc.; model 7010-D | 12 Vdc diaphragm pump, one for each filter (5) | 1-10 l/min | Volume regulated by voltage adjustment and microvalve | N/A |

N/A = not applicable.
[a] Units of measure for analog output voltages: mV = millivolts; Vdc = volts direct current; Vac = volts alternating current.

## Appendix 2
### Equations for Calculated Parameters

The equations presented below were used to compute the following parameters:

1. Carbon mass-balance-based fuel consumption.
2. Emission factor (EF) of emission n, for phase p.
3. Rate of fuel consumption.
4. Cumulative fuel consumption.
5. Rate of energy release.
6. Combustion efficiency.
7. Weighting of emission factors.
8. Calculation of PM10.

Emission factors were calculated from the mass of emission produced per mass of fuel consumed. The carbon mass-balance method was used exclusively to determine the mass of fuel consumed in producing the emissions. Basically, the carbon mass-balance accounts for the carbon released from the fuel during combustion by measuring the concentration of the carbon-containing combustion products.

The fuel consumed was computed based on the sum of $C_n$ from the combustion products as follows:

$$W_V = \frac{\left(\sum C_n\right)}{R}, \quad \textbf{(1)}$$

where,

*Wv* = fuel consumed, grams per cubic meter ($g/m^3$);

*Cn* = the carbon fraction of the emission n, $g/m^3$;

*n* = $CO_2$, CO, NMHC, $CH_4$, PM; and

*R* = the carbon fraction of the fuel elemental analysis.

It immediately follows that an EF for a specific emission, $E_n$, can be computed by dividing the mass of $E_n$ contained in a unit volume by the total fuel consumed in producing the emissions within the unit volume as follows:

$$EF_{np} = \frac{E_{np}}{W_v}, \quad \textbf{(2)}$$

where,

$EF_{np}$ = emission factor of the emission *n*, g/kg;

$E_{np}$ = concentration of emission *n*, milligrams per cubic meter; and

*p* = phase of combustion—F, S1, S2 or blank (if for entire fire).

The rate of fuel consumption during the fire was measured by the carbon flux technique. By measuring the concentration of carbon, converting the carbon to fuel according to equation (1), and multiplying the fuel per unit volume by the vertical velocity of the emissions, the resulting flux represents the rate of fuel consumption (with units of mass per unit area per unit time), as follows:

$$\dot{w} = (W_v)(V_z) , \quad (3)$$

where,

$\dot{w}$ = rate of fuel consumption, grams per square meter per second; and

$V_z$ = vertical velocity of plume, meters per second.

Cumulative fuel consumption is calculated by integrating the rate of fuel consumption curve from time i to j as follows:

$$W = \int_i^j w dt \approx \sum_i^j \dot{w}(t_{i+1} - t_i) , \quad (4)$$

where,

$W$ = total fuel consumed, grams per square meter; and

$t_i$ and $t_{i+1}$ = actual times during the fire of sufficient proximity so that $\dot{w}$ has not changed significantly.

The rate of energy release (reaction intensity) can be computed by multiplying the rate of fuel consumption by the heat of combustion, then subtracting the reduction in heat released from the compounds not oxidized completely. This heat release rate is calculated as follows:

$$I_r = \dot{w}\left\{H_f - \sum \left[H_n\left(\frac{EF_n}{1000}\right)\right]\right\} , \quad (5)$$

where,

$I_r$ = rate of energy release, kilowatts per square meter;

$H_f$ = heat of combustion, kilojoules per kilogram; and

$H_n$ = heat of combustion of emission n, kilojoules per gram.

Combustion efficiency ( $\Phi$ ) is defined in terms of the ratio of carbon converted to the most highly oxidized form—$CO_2$. It is a calculated parameter normally ranging from 0.60 to 0.95. If the carbon from the woody fuels were converted stoichiometrically to $CO_2$, then the emission factor for $CO_2$ would be 1835 g/kg. If the fuel undergoes

incomplete combustion, then a portion of the carbon is converted to other combustion products. Hence, the emission factor for $CO_2$ is reduced from the theoretical by the amount of carbon that is converted to other products (CO, $CH_4$, NMHC, and PM). By dividing the measured $CO_2$ emission factor by the theoretical $CO_2$ emission factor, the combustion efficiency can be calculated:

$$\Phi = \frac{EF_{co_2}actual}{EF_{co_2}theoretical} , \quad \textbf{(6)}$$

where,

$\Phi$ = combustion efficiency, dimensionless; and

$EF_{co_2}$ = emission factor for $CO_2$, g/kg.

Fire-weighted averages are emission factors averaged to represent an entire fire for a given emission subcomponent *n* (*EFn fire*). They were weighted based on the amount of fuel consumed during each of the sampling periods as follows:

$$EF_n fire = \frac{\left[(EF_{nF})(W_F) + (EF_{nS1})(W_{S1}) + (EF_{nS2})(W_{S2})\right]}{(W_F + W_{S1} + W_{S2})} , \quad \textbf{(7)}$$

where,

*n* = emission subcomponent,

*F* = flaming combustion phase,

*S1* = first smoldering combustion phase, and

*S2* = second smoldering combustion phase

PM10 is calculated as a ratio of the difference between the measured values of PM and PM2.5. The ratio is based on a small number of observations made from airborne sampling of large biomass fires and has not been verified for chaparral. The formula used to calculate the value of PM10 is as follows:

$$PM10 = PM2.5 + 0.17(PM - PM2.5) . \quad \textbf{(8)}$$

**Hardy, Colin C.; Conard, Susan G.; Regelbrugge, Jon C.; Teesdale, David R. 1996.** Smoke emissions from prescribed burning of southern California chaparral. Res. Pap. PNW-RP-486. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 37 p.

This report describes a comprehensive study characterizing the smoke emissions from small-scale prescribed burns in southern California chaparral. In situ measurements of smoke emissions were made from 12 fires. Three replicate tests were performed in each of four distinct fuel and treatment types. Emission factors for each treatment are presented and also are combined with data from previous tests for general application to fires in standing chaparral.

Keywords: Emission factor, prescribed burning, chaparral, smoke management.



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